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COAL CARBONIZATION

BY

HORACE C. PORTER, M.S., Ph.D.
Chemical Engineer, Philadelphia, Pa.

American Chemical Society
Monograph Series

BOOK DEPARTMENT

The CHEMICAL CATALOG COMPANY, *Inc.*

19 EAST 24TH STREET, NEW YORK, U. S. A.

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GENERAL INTRODUCTION

American Chemical Society Series of Scientific and Technologic Monographs

By arrangement with the Interallied Conference of Pure and Applied Chemistry, which met in London and Brussels in July, 1919, the American Chemical Society was to undertake the production and publication of Scientific and Technologic Monographs on chemical subjects. At the same time it was agreed that the National Research Council, in coöperation with the American Chemical Society and the American Physical Society, should undertake the production and publication of Critical Tables of Chemical and Physical Constants. The American Chemical Society and the National Research Council mutually agreed to care for these two fields of chemical development. The American Chemical Society named as Trustees, to make the necessary arrangements for the publication of the monographs, Charles L. Parsons, Secretary of the American Chemical Society, Washington, D. C.; John E. Teeple, Treasurer of the American Chemical Society, New York City; and Professor Gellert Alleman of Swarthmore College. The Trustees have arranged for the publication of the American Chemical Society series of (a) Scientific and (b) Technologic Monographs by the Chemical Catalog Company of New York City.

The Council, acting through the Committee on National Policy of the American Chemical Society, appointed the editors, named at the close of this introduction, to have charge of securing authors, and of considering critically the manuscripts prepared. The editors of each series will endeavor to select topics which are of current interest and authors who are recognized as authorities in their respective fields. The list of monographs thus far secured appears in the publisher's own announcement elsewhere in this volume.

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The development of knowledge in all branches of science, and especially in chemistry, has been so rapid during the last fifty years and the fields covered by this development have been so varied that it is difficult for any individual to keep in touch with the progress in branches of science outside his own specialty. In spite of the facilities for the examination of the literature given by Chemical Abstracts and such compendia as Beilstein's Handbuch der Organischen Chemie, Richter's Lexikon, Ostwald's Lehrbuch der Allgemeinen Chemie, Abegg's and Gmelin-Kraut's Handbuch der Anorganischen Chemie and the English and French Dictionaries of Chemistry, it often takes a great deal of time to coördinate the knowledge available upon a single topic. Consequently when men who have spent years in the study of important subjects are willing to coördinate their knowledge and present it in concise, readable form, they perform a service of the highest value to their fellow chemists.

It was with a clear recognition of the usefulness of reviews of this character that a Committee of the American Chemical Society recommended the publication of the two series of monographs under the auspices of the Society.

Two rather distinct purposes are to be served by these monographs. The first purpose, whose fulfilment will probably render to chemists in general the most important service, is to present the knowledge available upon the chosen topic in a readable form, intelligible to those whose activities may be along a wholly different line. Many chemists fail to realize how closely their investigations may be connected with other work which on the surface appears far afield from their own. These monographs will enable such men to form closer contact with the work of chemists in other lines of research. The second purpose is to promote research in the branch of science covered by the monograph, by furnishing a well digested survey of the progress already made in that field and by pointing out directions in which investigation needs to be extended. To facilitate the attainment of this purpose, it is intended to include extended references to the literature, which will enable anyone interested to follow up the subject in more detail. If the literature is so voluminous that a complete bibliography is impracticable, a critical selection will be made of those papers which are most important.

The publication of these books marks a distinct departure in the policy of the American Chemical Society inasmuch as it is a serious attempt to found an American chemical literature without primary regard to commercial considerations. The success of the venture will depend in large part upon the measure of coöperation which can be secured in the preparation of books dealing adequately with topics of general interest; it is earnestly hoped, therefore, that every member of the various organizations in the chemical and allied industries will recognize the importance of the enterprise and take sufficient interest to justify it.

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TO

THE MEMORY OF

MY MOTHER

Author's Preface

The economic phases of coal carbonization have been in need of an unprejudiced presentation, backed by careful elucidation of the underlying technology. Writings on the subject have been set out, on the one hand, by the economist, for purposes often of popular appeal, with resort to figures and arguments unsupported by experience; and, on the other hand, by able technologists, who, without intention, may have leaned to an economic or technologic view influenced by association or interest.

It has been the endeavor of the author of this book to avoid these viewpoints. Coal carbonization, in his opinion, cannot displace all, or even most, of the other forms of fuel application. It will grow until it supplies so much of coal by-products as are needed, and supplants less efficient and more costly fuel consuming methods. But it will not in all cases be less costly. Under many conditions, likely to prevail, the returns from by-products will dwindle, and costs of "processing" by carbonization will rise. By those conditions, governing part always of the power and heat producing field, the progress of this system of improvement of fuel will be checked, but it will go far in those fields where its virtues are practically applicable.

Coking and gas making at high temperatures—the industry of carbonizing coal in retorts at a bright red heat—is the subject given chief attention in this book. Another phase, namely, carbonization at the lower temperatures, wherein a different technique and different products are involved, is at this time attracting much attention as a new development in the world of fuel; but it has not, as this is written, attained or given assurance of attaining in the future such commercial success as to warrant assignment to a principal rôle in the presentation here made. This phase is treated fairly and with an open mind, but not with undue enthusiasm, nor a disproportionate allotment of space.

By-product coke ovens are described in detail. They predominate among coal-carbonizing devices and deserve therefore most prominent mention. Their predominance has been won by successful economic and industrial demonstration of a high degree of efficiency and a continued progress. Other methods may outstrip them, but at present they are in the lead.

Carbonization is a chemical process—and leads peculiarly to chemical research and the application of chemical principles and laws. The treatment herein, for the purpose of making fully clear the methods of large-scale industrial application, has added to the chemical and physical fundamentals, much description and discussion that partakes chiefly of an engineering character or has to do with industrial plant operations. In a work on chemical technology this is thought to be not out of place.

The fundamentals have not been neglected. The nature of coal, the mechanism of carbonization, the underlying principles of the cooling and scrubbing of vapor-carrying gases, and the transfer of heat through refractory walls into a subdivided, loose-lying mass of coal, undergoing decomposition,—these and other scientific phases of the subject receive such attention as to assure the reader firmly of their importance.

A general discussion of the gas industry and its future has been introduced, as, by this avenue, there appears to be opened the most inviting prospect for expansion of industrial coal carbonization beyond the confines of metallurgical coke manufacture.

There is rapid progress of development in the methods of coal carbonization, and in the clarifying, by research, of scientific facts and principles, concerned therein. Much that is written today needs amplification tomorrow. But the reader, understanding this and appreciating that the subject, by its nature, involves little that is complete except the laws and principles on which it rests, will be indulgent, it is hoped, with features that will assume in perhaps a short time a character of obsolescence.

Some readers will be disappointed to find herein only a brief account of such important carbonization products as coke, tar and ammonia,—their uses, commercial treatment, derivatives, and properties. There is no valid excuse for this deficiency, except that branches, such as these, grow too large to form a well-proportioned tree. Their importance, and the wealth of detail to be set out in their thorough development, justifies and properly requires, for that purpose, separate treatment.

To Professor S. W. Parr, of the University of Illinois, valued teacher and friend, who has been a pioneer and leader of research in America pertaining to coal carbonization, the author wishes to express his especial obligation for helpful suggestions throughout the work.

Acknowledgment is gratefully given to the Semet-Solvay Co. and The Koppers Co. for much of the descriptive data and illustrative material pertaining to by-product coke ovens; to the Foundation Oven Co., New York; the American Coke and Chemical Co., Chicago (Roberts ovens); the Gas Machinery Co., Cleveland; the Belgian-American Coke Ovens Corporation, New York (Piette ovens); and to Piron Coal Distillation Systems, Inc., New York, for courteously furnishing data and drawings of the special equipment marketed by each.

For advice and assistance in preparation of the chapters on by-product coking especial acknowledgment is due and gladly given hereby to Wm. H. Blauvelt and Murray Hastings (of the Semet-Solvay Co.); Joseph Becker, Jos. VanAckeren, and H. B. Kirkpatrick (of The Koppers Co.); J. W. Shaeffer and E. F. Burdick (of the Milwaukee Coke and Gas Co.); F. F. Marquard (Carnegie Steel Co.); Geo. C. Lowell (Peoples Gas Light and Coke Co., Chicago); M. W. Ditto and M. D. Curran (St. Louis Coke and Iron Co.); Wm. Tiddy (Chief Chemist) and R. W. Heffner (Superintendent), Rainey-Wood Coke Co.; J. R. Campbell, Chief Chemist, H. C. Frick Coke Co.; and the many plant superintendents of coking establishments by whom the author has been accorded uniformly courteous reception on numerous visits of inspection.

In connection with gas manufacture and by-products helpful information, accompanied by valuable original drawings and other illustrative material, has been given by the Isbell-Porter Co. (Woodall-Duckham retorts); the West Gas Improvement Co. of America (Glover-West retorts); J. H. Taussig and O. B. Evans, of the United Gas Improvement Co., Philadelphia; the Meriden (Conn.) Gas Light Co.; New Haven (Conn.) Gas Light Co.; Chas A. Lunn, Chief Chemist, New York Consolidated Gas Co.; W. H. Fulweiler, Chief Chemist, United Gas Improvement Co.; F. W. Sperr, Jr., Chief Chemist, The Koppers Co.; C. H. Stone, Laboratory Director, Rochester (N. Y.) Gas and Electric Corporation; S. R. Church, The Barrett Co.; C. C. Tutwiler and J. Ed. Brewer, West Conshohocken, Pa.; and the management of the American Gas Association.

The Jefferies-Norton Co., of Worcester, Mass., has made valuable suggestions for elaboration of the section on use of oxygen in gas manufacture.

Emil Piron and V. Z. Caracristi, of New York, inventors of the low-temperature carbonizing process bearing their names, which is being installed on a large commercial scale for the Ford Motor Co., have furnished full and valuable information on their process with original illustrative material.

To Professor J. W. Cobb, University of Leeds (England), and to Dr. R. V. Wheeler, Director of the Home Office Experiment Station, Eskmeals, the author is indebted for furnishing late reports of their investigations.

Others who have coöperated in this work are Philip S. Smith, Acting Director, U. S. Geological Survey, Geo. H. Ashley, Director of the Penna. State Geological Survey, R. S. McBride, Engineer-Chemist, and Alfred I. Phillips, Gas Engineer.

Philadelphia, Pa.,
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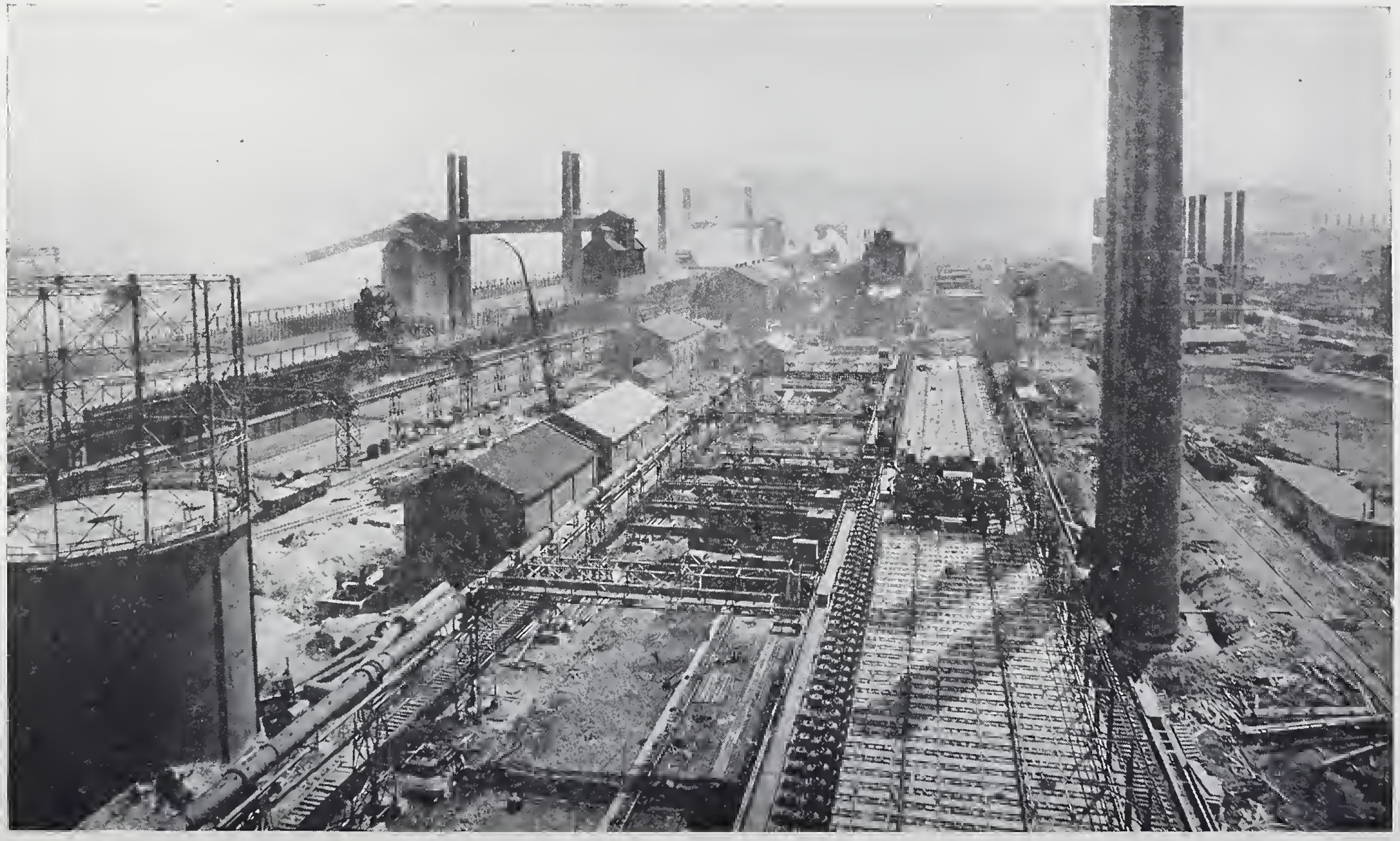

The Largest Coal Carbonization Plant in the World; By-Product Coke Works of the Carnegie Steel Co., Clairton, Pa., 1134 Ovens in Three Rows, 18 Batteries (of which 366 ovens, in foreground, are under construction).

Introduction.

By Samuel Wilson Parr

(Professor of Applied Chemistry, University of Illinois)

The future historian, reviewing the scientific and industrial developments of the period covered by the closing years of the nineteenth and the opening years of the twentieth century, will have a most interesting story to relate. Because of proximity, we are just now at a disadvantage in not being able properly to evaluate the events through which we are passing. We have not the necessary perspective —in other words, we lack the widening range of vision that brings into our estimates a more extended list of events from which to establish comparative values.

In pure science, for example, the atom has been rediscovered, the electron has been put on the map, and the ether has been given something to do. Pure Science has finally come to recognize Applied Science as one of her children, and in some industries Applied Science has really discovered herself, in that she, too, can now trace out and distinguish her own family relations. Pure science as a factor in development, improvement, and expansion along many lines of industry is a marked characteristic of these passing years.

One of the industries, however, has been very slow. We have recently celebrated the one hundredth anniversary of the achievements of Murdoch of England and Lebon of France in establishing the gas industry in their respective countries. In our own country we may be said to have just completed our first one hundred years, and although the first gas company was incorporated in the United States at Baltimore in 1819, at Boston in 1822, and in New York in 1825, it was not until the close of the nineteenth century that any notable advances over the initial discovery of the process of carbonization by Murdoch and Lebon were in evidence. That is to say, for substantially seventy-five years the carbonization of coal was carried on in the same way as at the outset, with small attention to modifications or improvement.

Now this is all the more strange when we recall that meanwhile an entirely new science has sprung up, based upon one by-product of the carbonization process—namely, the tar. And although we are indebted to the coke industry for tar, we go far away from that environment to locate the credit for dyes, explosives, synthetic medicines, antiseptics, perfumes, plastics, photographic reagents, and an almost endless list of substances that minister to our present-day needs.

This dormant condition of the carbonization industry for so many years cannot be ascribed to simplicity of the processes involved or a shortage of problems needing solution. On the contrary, it might more properly be assumed that the very complexities which characterize every phase of the work may have operated as a deterrent in the matter of attempts at their solution.

But whatever explanations we may bring forward for the apathy of the industry during the first seventy-five years of its existence, they have in these recent years disappeared or become inoperative. Doubtless the reasons for this change are numerous. The accentuation of the smoke evil in large industrial centers has set in motion numerous investigational activities looking to its abatement. Sooner or later these studies lead back, for a solution, to the carbonization of coal and the supplying of smokeless fuel in some form.

It is an old and familiar story. In 1550 Queen Elizabeth prohibited the burning of coal in London during the Parliamentary season for fear "the health of the knights of the shire might suffer during their abode in the Metropolis." The first smoke abatement commission was organized by the British government in 1819. A number of reports from similar committees were issued, culminating in the Public Health Act of 1875, and, notwithstanding this, a recent report of the London health officer (1915-16) estimates the annual deposit of soot for that city at 55,000 tons. A figure of this magnitude is not possible of comprehension unless reduced to some value within the reach of our appreciation. Let us say, then, from six to eight pounds of soot per person per annum, or one-half pound per month. Of course, it cannot be assumed that this material is able to focus itself directly upon the individual person, but yet, distributed as it must be, no argument is necessary to prove that the average individual receives his share. A recent report from the Mellon Institute estimates the annual soot fall for Pittsburgh at from 600 to 2,000 tons per square mile, and in the report of the special commission of the Chicago Association of Commerce (1911) the statement is made that "the Committee finds that domestic fires, including furnaces in apartment buildings, produce 57 per cent. of all the soot or tarry products of combustion discharged in the atmosphere of Chicago, and, for this reason, constitute the most objectionable source of atmospheric pollution in the city. Soot is shown to be damaging to clothes, property, and vegetation. . . . Visibility of smoke, which has been the sole object of complaint and regulation, is a matter of secondary importance:—that injury to animal and vegetable life and to property is due almost wholly to the invisible gases and solids emitted, and this is the big thing to be overcome." It may be noted in passing that Pittsburgh and Chicago have no difficulty in keeping pace with London in this particular matter of soot apportionment.

One cannot review the history of coal carbonization without being impressed with the fact that an initial and fundamental idea running throughout all the activities has been the paramount one of promoting the comfort, health, and economic betterment of the public by substituting some more efficient medium than raw coal for the generation of heat. None the less, the entire way behind us is sadly smudged over with soot, and we are all eager to know if clear skies and sunshine are ahead. Well, the prophets in this realm are all optimists. So famous a one among them as Sir William Siemens wrote in 1881:

"I am bold enough to go so far as to say that raw coal should not be used as fuel for any purpose whatsoever, and that the first step toward the judicious and economic production of heat is the gas retort or gas producer in which coal is converted either entirely into gas or into gas and coke."

In spite of such prophecies, we still have, forty-four years after, smoke and soot, and soot and smoke.

But things have been happening. The by-product coke oven has come upon the scene. Natural gas and oil have come forward creating a host of devotees who want their fuel in mobile—that is to say, smokeless—form. Most noteworthy, however, is the fact that highly trained specialists have entered the fuel field and are devoting their energies to a solution of the riddles there embedded, and so, by solvents and heat and fractionation and the microscope, we are just beginning to understand some of the first letters of the alphabet pertaining to coal constitution and carbonization, coke formation and structure, fuel combustion in general, and complete gasification in particular as an ultimate goal—at least for the seers, the dreamers of dreams.

Every industry has its periods of transition. No greater service can be rendered at such a time than to assemble and make available all the data and established facts pertaining to the entire range of activities involved. That such a service has been rendered to the coke and gas-making industry by this monograph will be a very positive impression on the part of any one making use of it as a source of information. The author is peculiarly well fitted by both training and experience for his task and as a result there has been brought together a fund of information not otherwise accessible in any compact and convenient form. His treatment of the entire field has been impartial, conservative, scientific, and both the author and the industry are to be congratulated on the result.

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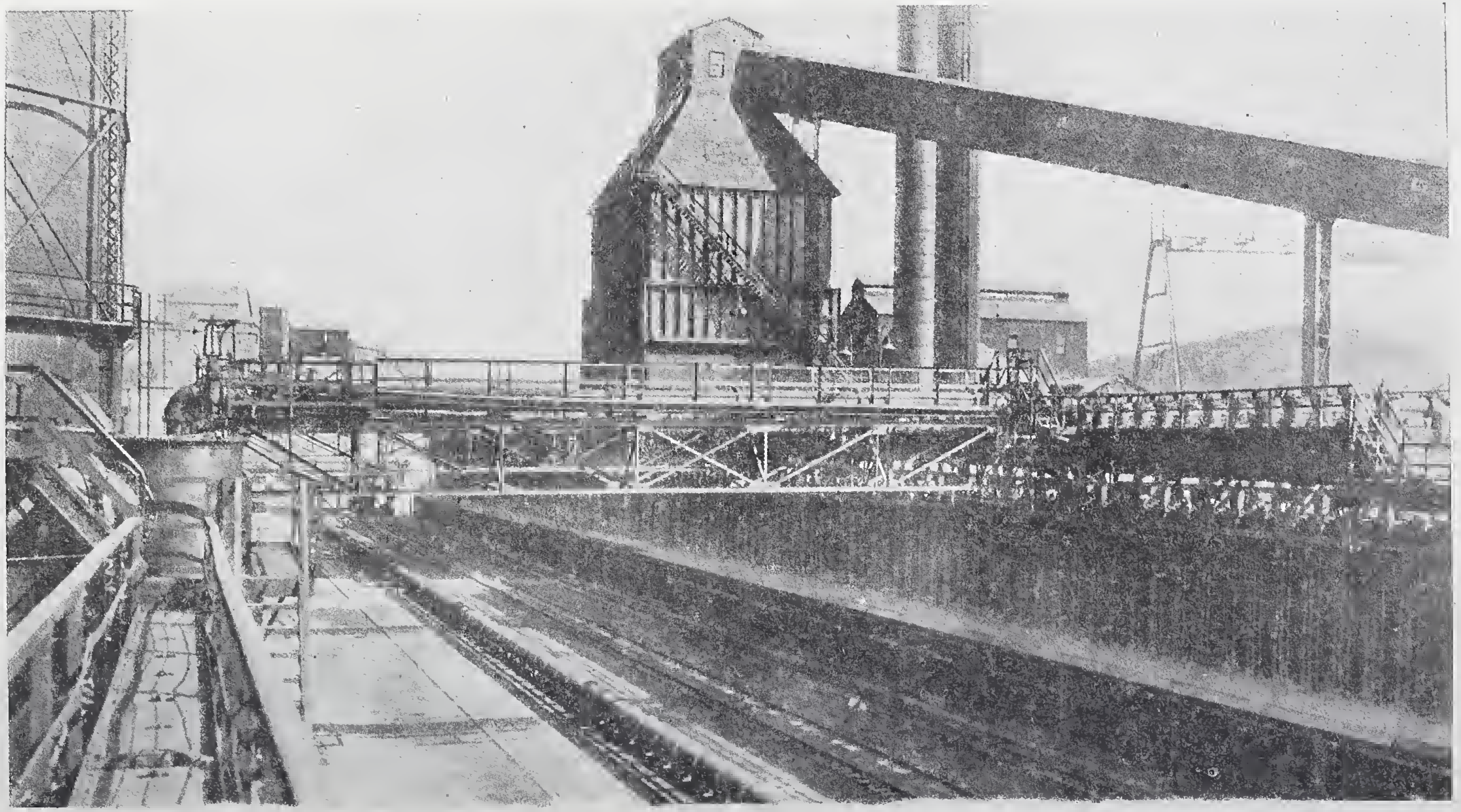

FIG. 1.—View of the Oven Batteries, Typical By-Product Coke Plant, of Medium Size. (Crossover main, bearing gas-governor, in foreground.)

COAL CARBONIZATION

Chapter I.

Introductory.

Present and Future of Coal Carbonization.

Coal carbonization means, industrially, the making of coal-gas, coke, and by-products; also, as recently brought much to the fore, "semi-coke," a proposed clean, smokeless, general fuel, obtained by carbonizing at moderate temperatures.

Carbonizing, or "baking" in highly heated ovens without air, converts, in popular parlance, the "smoke" of the coal into gas and by-products, leaving coke, a solid, porous, smokeless fuel, as residue.

Scientifically, coal carbonization is destructive distillation, decomposition by the agency of heat, without air, causing increase of carbon content, at the expense of other constituents volatilized in the gases. Coal is a plant material, the metamorphosed remains of vegetation. It is made up of a number of complex compounds, into which enter chiefly carbon, hydrogen, oxygen, nitrogen and sulphur. These compounds, like most of those in vegetable and animal life, are unstable when subjected to a high degree of heat. They break down to form gases and a "carbonized" or carbon-enriched residue. But in the coal, free carbon is not present, and mineral constituents (other than the original plant "ash") are adventitious—incidental.

Coal carbonization is of much industrial importance, growing into greater prominence as coke and gas are found increasingly useful. One hears much of "by-products"—a magic word to compel popular interest. Through them, a genius of industry or of science is put forward repeatedly, in the popular announcements, as about to draw immense profits from new methods of applying fuel. In truth, there are by-products to be had, and their value is large, but too often in the promotion of new schemes of this sort, the costs of the conversion, as related to the values of the by-products gained, are inadequately set forth.

The present extent of the industry of coal carbonization, detailed later in these pages, is such as to command a great deal of respect. It is not a minor industry.

Gas and coke, in many industries, are accepted as superior fuels, economical in relation to raw coal notwithstanding their higher cost. A huge steel mill can be run entirely by the energy derived from its coke making establishment, where the coke, necessary for smelting the ore, is produced. Such procedure as to fuel supply is in fact frequently advocated for such mills. In the use of blast furnace coke, blast furnace gas, coke oven gas, coal-tar and coke breeze, the mill finds its fuel requirements completely met.

Many and varied metal-working and other industries, too numerous to list, where the heating furnace is an important factor, find gas fuel in these furnaces economical and advantageous.

Manufactured gas for public distribution, whether for industrial or domestic consumption, is largely a product of coal carbonization. The householder will use gas in increasing measure, as there comes to be applied a more rational system of charges and more economical methods of manufacture, reducing its cost. He will turn away as fast as he can from the use of raw coal in his house, destined some day to be regarded as a relic of primitive and barbarous times.

Coal carbonization is a process of modifying a crude, raw fuel into better fuels, of extracting valuable by-products,—ammonia, light oils, and tar,—before they are destroyed in the burning, of converting the raw, smoke-producing inefficiently-handled coal, into the clean and smokeless gas or coke, efficient in use and in distribution. Rational and scientific methods of meeting the problems of this development, of saving the maximum of values from the raw material, with minimum costs of conversion, are being vigorously applied. They open alluring vistas for scientific research and industrial coördination.

There can be only the question of time in bringing about, by this means, a remarkable revolution in methods of fuel application. The efficient, clean, and systematic methods will prevail, and through the distribution of gas, carbonized fuels and electricity (the latter made in large central stations from coal by improved methods), the ultimate consumer of energy as heat or power will be able to abandon, in a large measure the direct application of raw coal.

The ideal to be striven for in coal carbonization is to reduce to such a point the outlay of heat energy and conversion expense in the process, and raise to such a point the yields and values of products, that a margin entirely safe is established under which this fuel-applying method may generally prevail.

Chimerical it may seem to many, but unquestionably it is within the bounds of possibility that our coal consumption, in the course of a generation or two, may be 50 per cent. or more through the medium of carbonization. On such a scale, in America, could be made thereby 100,000,000 barrels of Diesel engine oil, 20,000,000 barrels of light motor fuels, 2,000,000 tons of sulphate of ammonia—sufficient nitrogenous fertilizer to release the nation from dependence on Chile saltpeter. The possible outgrowth of chemical manufactures from

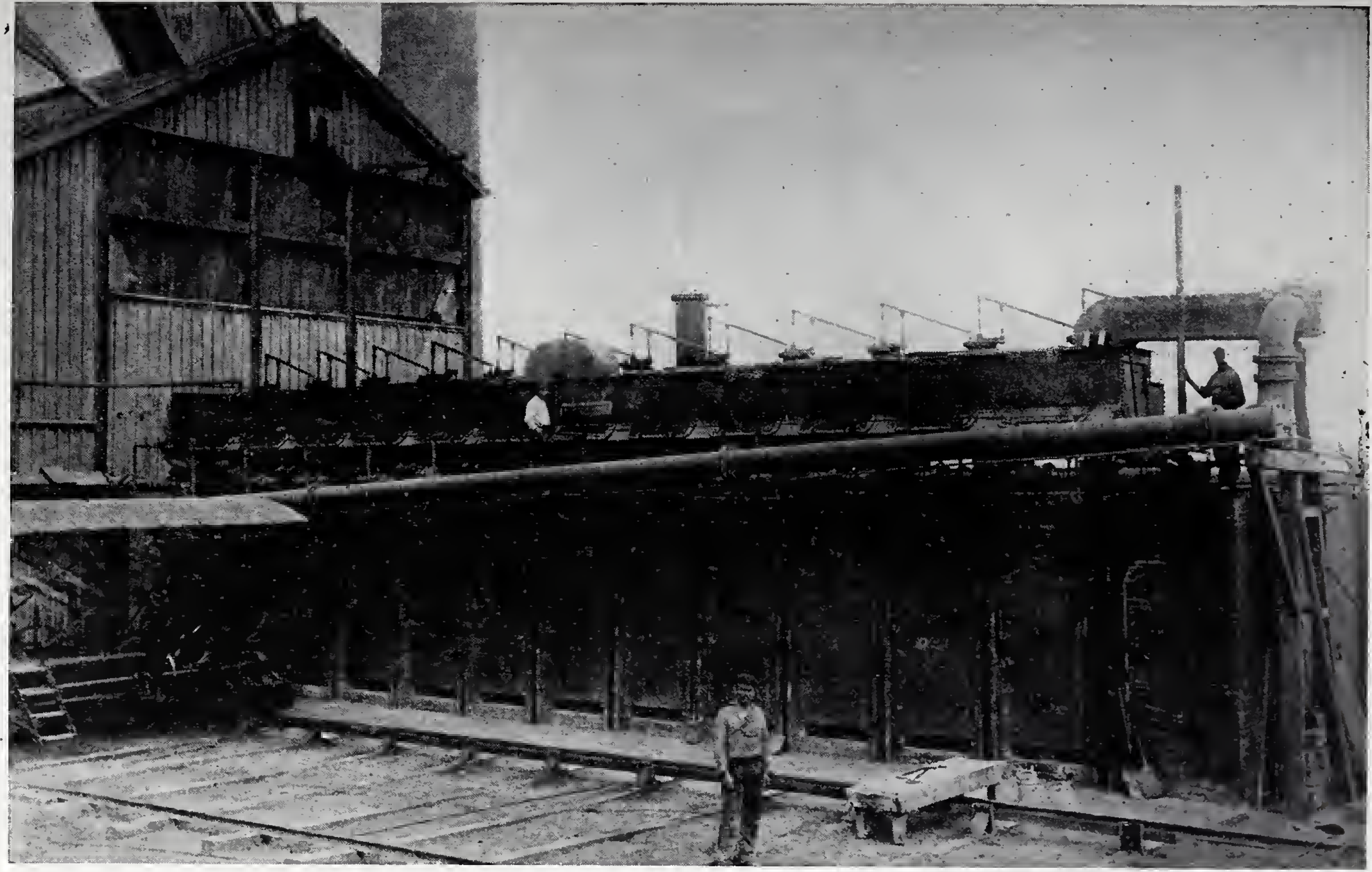

Fig. 2.—Original By-Product Coke Oven Plant in America—Twelve Semet-Solvay Ovens at Syracuse, N. Y., built in 1893. (Pusher-side View.)

the tars of coal, the old and the new, is a mine of golden opportunities to the research chemist. The field has been only lightly touched.

Developments in coal carbonization have been moving swiftly in recent years, and strong, well-directed, persistent effort is carrying them on. They are sure to reach practical results of far-reaching value in the world's civilization.

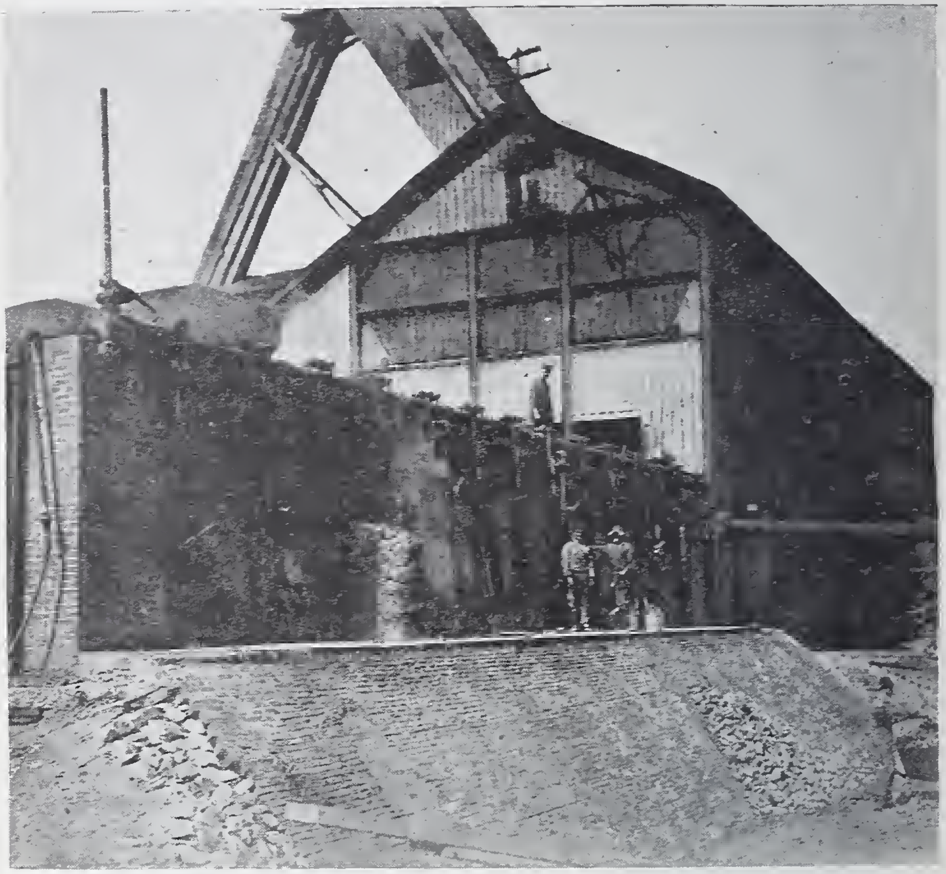

Fig. 3.—Original By-Product Coke Oven Plant in America—at Syracuse, N. Y., Coke Side View, Showing Early Method of Quenching and Handling Coke.

Chemistry and Carbonization. Carbonization is essentially a chemical process. In its fundamentals it involves principally chemical changes. The coal is transformed in such manner that none of its original components remain as such in the products, unless it may be part of the incombustible matter and a very small amount of certain occluded gases. The secondary reactions proceed according to physico-chemical laws. The industrial treatment involves chemical principles and requires chemical control. We therefore properly class a discussion of the principles of coal carbonization and description of the methods of their application as essentially a chemical treatise.

The Products of Carbonization. From a ton of coking coal, of 2,000 pounds, there are obtained, as a general average in "high temperature" carbonization, the following products:

1,400 pounds of coke,
10 gallons of tar,
5½ pounds of ammonia, or
22 pounds of sulphate of ammonia,
3 gallons of light oil,
11,000 cubic feet of total gas, or
6,000 cubic feet of surplus gas (the surplus over and above what is used to effect the carbonization process by supplying heat to the ovens).

The yields, both in weight and in heat units (B.T.U.), based on the coal as 100 per cent., are shown in Figure 4.

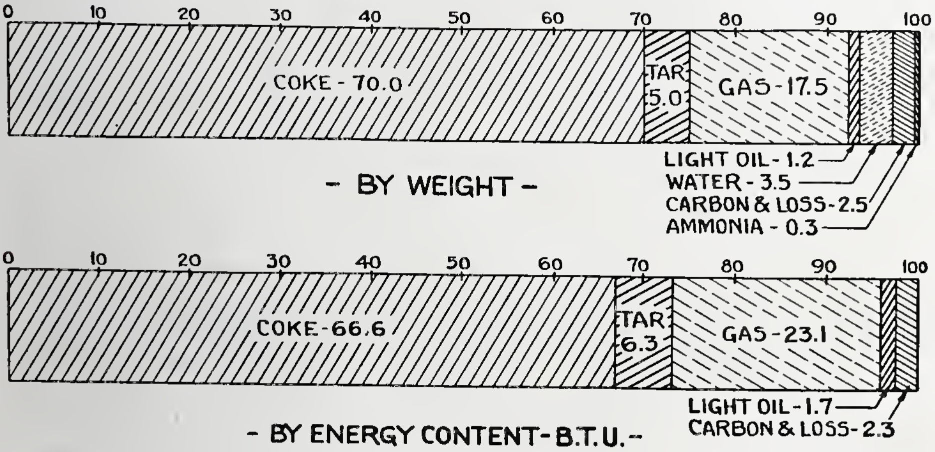

FIG. 4.—Average Percentage Yields of the Products of Coal Carbonization (at High Temperatures).

In carbonization none of the material is consumed, or disseminated into the atmosphere, as in combustion. Theoretically the weight of material remains constant, although in practice small losses are unavoidable. The original energy also is conserved—in the total of that available in the products plus what is dissipated to the surroundings by radiation and conduction from apparatus and heated products.

Practically, in the energy balance, the recoverable products show a loss. They have, in the aggregate, materially less heating value than the coal from which made, and indeed it is not to be expected, in view of the many chemical changes occurring, that the available energy in the products would remain the same. Heat balances drawn from operating data have often been used as a basis for the conclusion that part of the original potential energy of the coal disposes itself in the heat of exo-thermic reactions during carbonization, this heat being lost by radiation or in the sensible heat of the products. Owing to the difficulty of securing an accurate materials balance in carbonization on the large working scale, and of measuring accurately all of the increments and losses—both of materials and of energy—such conclusions are often drawn too closely and disregard the relatively great magnitude of the probable error involved in the experimental method. (See further, in detail, on this subject, pages 244-6.)

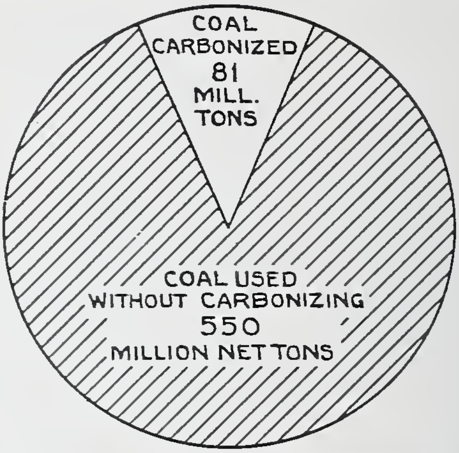

FIG. 5.—Proportionate Quantity of Coal Carbonized and Total Coal Used in the United States (1920).

The Present Extent of Coal Carbonization. About 81,000,000 net tons of coal were carbonized in the United States in 1920, somewhat less than one-sixth of the coal (anthracite and bituminous) that was burned in the raw state. (Figure 5.) The value of the products, at point of consumption (counting gas at its value to the ultimate consumer), was in round numbers $750,000,000, or, in the industry as a whole, $9.25 per ton of coal carbonized.[1]

The industry, therefore, forms a large part of the fuel-utilization scheme. The products, up to the present time, however, have commanded principally a specialized market. Easily two-thirds on a basis of value, is absorbed for the purpose of smelting iron ore. The use of coal carbonization for general fuel purposes, to make fuels for

[1] *U. S. Geological Survey,* Mineral Resources of the United States, 1920, Part 2, Chapter 35, "Manufactured Gas and By-Products in 1920," by R. S. McBride. From data on pages 439-440 of this report, the value of the coal gas, coke oven gas and all by-products sold in 1920 (not including water gas and oil gas), is deduced as $164,000,000. The value of coke oven gas is therein taken only at the wholesale price (averaging 14 cents per 1,000) obtained by the producer, but (page 445) about one-fourth of the coke-oven gas sold went into public utility distribution where it commanded a much higher price from the ultimate consumer, probably the same as that given for coal gas or 91 cents per 1,000. Hence, on this basis the valuation of the coke oven gas must be increased by an amount approximating $45,000,000 and the total value of gas and by-products then becomes $209,000,000. The total value of coke produced in the United States in 1920 (Mineral Resources, 1920, Chapter 34, page 367) was $494,246,000 at the ovens. This value, it may be assumed, became at least $541,000,000 by the time

domestic and industrial heating and power, has made hardly more than a start.

As little as 1 per cent., or less, of the total solid fuel used, aside from that applied to the smelting of ores, is coke, charcoal, or other solid product of carbonization. The sales of manufactured gas (Figure 6), although they have made rapid growth during the last 15 years, constituted in 1920 (with inclusion of water gas) only 2 to 2½ per cent. of the total raw coal consumption on a heat-unit basis. Yet, the quadrupling of consumption of manufactured gas, in 15 years, is indicative of the growing demand for fuel of convenience and efficiency, and portends a future growth for which it will be difficult to provide adequately the equipment for production and distribution.

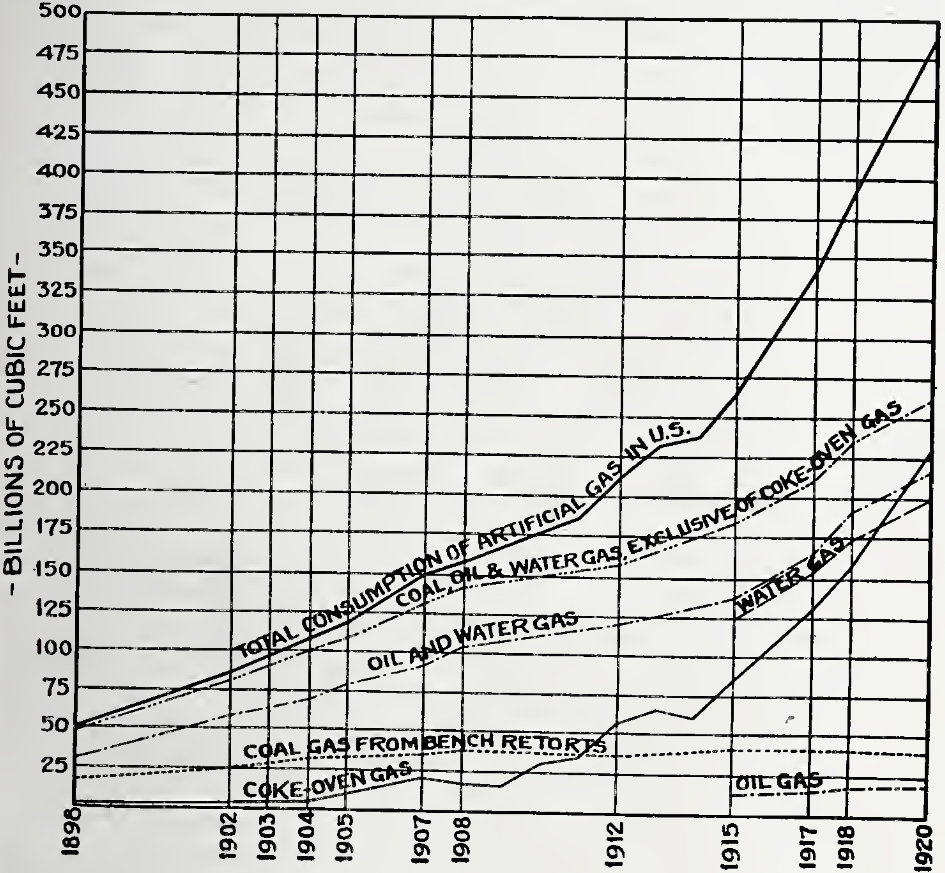

FIG. 6.—Growth of the Sales of Manufactured Gas in the United States (diagram by U. S. Geological Survey, R. S. McBride).

the coke reached the final consumers, and with the total value of gas and by-products ($209,000,000) above noted, formed the grand total of $750,000,000.

In the by-product coking and coal gas industries (omitting bee-hive coking), about 49,000,000 tons of coal were carbonized in 1920, and products obtained with a value of $539,000,000 at point of consumption, or about $11.00 per ton of coal carbonized.

Why Resort to Carbonization? The question naturally arises—What justifies coal carbonization, in view of the fact that transformation of raw coal, by this means, costs, for heat outlay, plant investment and operation, 40 to 45 per cent. of the value of the coal? Are the products, as fuels, to that extent enhanced in practical value, when applied generally, or are they enhanced only in certain limited and specialized fields? Is it due to the by-products—tar, light oil, and ammonia—and to their value outside of the fuel field, that the account can be balanced and a profit won?

These questions are given consideration in the following chapters, with data which may assist in deriving answers. It appears that up to the time of this writing the inducement, in the shape of assured profit throughout an adequate period, has been lacking, to encourage large expansion of the coal carbonization industry outside of the special field of metallurgical fuel.

The gas industry has grown rapidly, by virtue principally, of the rapid growth of by-product coking in the metallurgical field, gas being a by-product. The growth of demand thus begun, especially in the field of industrial fuel, is likely to lead on, beyond the limited production incidental to the making of metallurgical coke. If regulated, however, as a public utility by public service commissions, large growth in the general application of gas fuel in the industries (outside of the manufacturer's own plant), can come only through the permitting of standards of gas quality that conform to maximum economy in manufacture, distribution, and use. In that way costs and prices are lowered and consumption stimulated.

Limitations in the Applicability of Coal Carbonization. For steam power production, through the medium of coke and gas as fuels, with the recovery of by-products, coal carbonization does not, under present conditions and methods, offer great promise of success. Its thermal efficiency, over-all, from raw coal to steam, is as yet too far below that of direct coal burning, to allow a balancing of accounts through sale of the by-products. It is only as applied in certain limited fields that gas and coke have the necessary enhanced value, with addition of the revenue from by-products, to pay the costs of carbonization. These fields will be enlarged as the costs of this method of modifying coal are reduced. There is some promise in new processes such as low temperature carbonization that may increase the returns from by-products and by this means reduce the net cost for thermal units or available fuel in the products. But, as this is written, no such process has yet demonstrated its ability so to do in commercial trials.

The field of coal carbonization yet remains limited, but it is a field that is full of potentialities for development and for widening of scope, in proportion to progress in reduction of the expense of the process.

Importance of the By-Products in Coal Carbonization. The by-products, ammonia, tar, light oil, and (on coke oven plants) surplus gas, are of such importance financially to the business of coal carbonization, that their efficient recovery and disposal generally determines the success of the plant. Their revenue, if gas be included, covers ordinarily the costs, for plant investment and operation.

But extravagant estimates of values resting in the by-products, as related to the cost of the coal, are frequently made by those who decry the prevalent waste of coal resources. These estimates disturb rather than promote progress in extending the use of coal carbonization.

Values, for example, of by-products based on delivery prices of refined materials, including the high costs of manufacture and distribution, cannot properly be set down as a measure of the economic loss incurred through a simpler use of the raw material without by-product recovery. Costs of manufacture and delivery should first be deducted.

When thus conservatively estimated the value of the by-products of coal carbonization, including surplus gas, may usually be placed at 35 to 40 per cent. of the cost of the coal (both based on values at the plant). Their recovery cannot be considered as a clear gain, in that degree, over the direct application of raw coal, since the losses and costs in carbonization must be taken into account.

For these reasons the undertaking of coal carbonization primarily for the recovery of by-products and without adequate disposal of the coke, will not succeed unless by-products are to attain greatly increased values.

Conservation Through By-Product Recovery. On grounds of conservation of natural resources, especially of the nitrogen in coal, the displacement of raw coal consumption by carbonization makes more of an appeal. Millions of tons of nitrogen go to waste each year through combustion of raw coal. But if the substitution of carbonization, gasification and by-product recovery for the burning of coal raw results in the requirement of more coal and more equipment and more capital, as seems probable from estimates of present available processes, in connection with steam power production (pages 51-2), then conservation of the one resource—nitrogen—is costly when obtained only by expenditure of another, the heat resource of the coal itself. In fields other than that of power production, however, the by-product method is being found practicable, and more and more profitable.

The By-Products in War. The demand for coal by-products is immensely increased by war. They are so essential that it behooves a nation desiring military preparedness, to take account of its coal-carbonizing industry and in time of peace to encourage expansion therein to the maximum economically practicable.

Wars are won, it has been said, by coal and iron. It is unquestionably true that coal by-products are an absolute essential in modern military high explosives, as well as in many of the so-called poison gases of warfare. Without them, under present known methods of supply, shell warfare could not go on.

Benzene and toluene, obtained from light oil and tar, are converted by nitration (the former through an intermediate compound, phenol) into picric acid and tri-nitro-toluol (TNT). These were practically the only high explosives (with exception of ammonium nitrate, in admixture) which had important application as bursting charges during the last Great War. At the close of that war the United States was equipped to furnish 22,000,000 gallons of toluene per year, equivalent to 300,000,000 pounds of TNT.

Ammonia also, which is obtained in large amount from coal carbonization, is highly important as its nitrate in military explosives. The fixation of atmospheric nitrogen, to form ammonia, is established on a large scale in European countries, notably Germany, but in the United States it has made only a small beginning, commercially successful. During the Great War the ammonia used by this country in high explosives was derived almost entirely from coal carbonization.

Coal, the Mainstay for Fuel and Power. That the United States for many years will depend chiefly on coal as a source of power and heat, is shown in the chapters following. To meet the rapid growth of demand, in the expansion of industry and the raising of standards of living, improved efficiency in utilization of coal will largely be depended on to forestall the increase in rate of depletion of the reserves. Consideration of these matters, and especially of the part that carbonization may play in the accomplishment of this economy, is enlarged upon in the succeeding pages.

The Subject Treatment Herein. There is presented in the following chapters mainly a description of the industrial equipment for coal carbonization, of the methods of its operation, and of the products, together with an outline of the principles underlying the practical application of carbonization. Prefacing this, is a discussion of the economic aspects of coal carbonization and résumé of the theory of what goes on in the coal substance during carbonization.

By-product coking is described at length, and a place of prominence relative to the other methods is given it throughout. This is for two reasons, (1) because by-product coking, on the basis of capital investment and value of the products, constitutes 75 per cent. of the coal carbonization industry in America, and (2) because it appears likely that by-product coking will continue to hold for a long period a similar or better position of prominence, as a result of the abandonment of the bee-hive method of coke making, and in conformity with the expansion of the use of gas and other carbonization products for industrial and household fuels.

The engineer designing, building, or operating a coal carbonization plant will not find this a manual fulfilling all of his requirement of information. The book is intended more particularly for the average technically trained man, chemist, business executive, or engineer, who requires a knowledge of the principles and an outline of the practice in coal carbonization.

Chapter 2.

Fuels and Power.

Sources of Energy. For the industries the possible sources of energy are:

1. Water power;
2. Coal, lignite, peat and wood;
3. Oil;
4. The sun's rays;
5. The tides.

The two latter may be omitted from consideration of sources immediately practical, owing to their cost and limited application. On water power, coal and oil, will rest the burden for many years.

It is pertinent, therefore, in this connection to analyze the resources of these three that are available, and in case of coal, the principal one, to study by what methods best to apply it with a view to conservation.

Oil, in the United States, is relatively a small resource. It has been consumed, according to some authorities,[1] to the extent of 40 per cent. of the estimated original amount practically available and offers a recoverable remainder still underground, equal to about 7 billion barrels, enough to last but 15 to 20 years at present rate of consumption. It would last 9¼ years if applied to the entire present power load.[1]

Other authorities [2] estimate the quantity of petroleum still available in the fields of the United States as from 3 to 4 times that named above, on account of the probable future improvement in percentage of extraction from the sands. The probable life of the reserves also is capable of being increased through improved efficiency in methods of use.

The consensus of expert opinion [3] would indicate a probable life of the petroleum reserves in this country of between 30 and 100 years, assuming a gradual improvement in percentage of extraction and an increasing reinforcement by foreign importation.

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[1] Geo. Otis Smith, "Industry's Supply of Energy," *Mechanical Engineering*, 43, 165-6 and 188 (1921).

[2] For example, J. O. Lewis (formerly in charge of Petroleum Division, U. S. Bureau of Mines) in *Journal of Franklin Institute*, 191, 357-79 (1921), "America's Petroleum Problem."

[3] In Press Notice No. 12,198 of the U. S. Geological Survey, 1922, estimates are given of the oil supply of the United States by a joint committee of oil geologists representing the American Association of Petroleum Geologists and the U. S. Geological Survey. This estimate places the recoverable reserves, using present methods, at 9,150,000,000 barrels, and states that they "are enough

Water power, whose great virtue lies in the fact that by development and use it does not become exhausted, is estimated as available [4] throughout the nation in the amount of 50,000,000 horse power (without the provision of storage to take care of the periods of interrupted flow). It could be increased to 60 or 65 million horsepower by the provision of storage. The water power of the country, fully developed and used at 30 per cent. load, would take care of the present power requirements of industry, *if suitably distributed.* Geographical distribution of this resource, however, in relation to the energy demand is, under present conditions, at fault.

The relation may be expressed as follows: [5]

TABLE 1.

	Potential Water Powers H-P	Per Cent. of Total	*Equivalent* Available Energy in Water Powers (Millions of H-P-Hours)*	*Total Energy* Utilized in Primary Power 1915 (Mill. H-P-Hours)†	
New England States..	1,951,000	31.4	49,036	Steam	110,000
Atlantic States	9,348,000			Water	15,000
Central States	7,360,000				
				Total	125,000
Mountain States	14,851,000	68.6	106,962	Steam	2,500
Pacific States	25,850,000			Water	7,000
				Total	9,500
Total United States...	59,360,000	100.0	155,998		134,500

* On basis of 30 per cent. load factor.

† Does not include consumption of energy (as coal, etc.) for the heating load, industrial and domestic.

It is apparent that, as far as the Western States are concerned, the available water powers (fully developed and used on 30 per cent.

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to satisfy the present requirements of the United States for only 20 years, if the oil could be taken out of the ground as fast as it is wanted." The reserve, however, cannot be drilled and pumped dry in 20 years, or even in 30 or more, and the demands of this country therefore will necessarily be met in part from other sources during the remaining life of the domestic reserve.

[4] Geo. Otis Smith, *loc. cit.; Electrical Review* (Anon.), 77, 366-8 (1920); Philip Torchio, *Jour. Amer. Institute of Elect. Eng.*, 39, 315-23 (1920).

[5] Adapted from data of *Electrical Review* (Anon.), *loc. cit.;* Philip Torchio, *loc. cit.*

load), would have approximately 10 times the capacity needed to meet the present power requirement of industry in that section, assuming that distribution within that section could be fully accomplished.

On the other hand, in the central and Eastern states, the available water powers used under 30 per cent. load, can meet scarcely 40 per cent. of the present primary power consumption in that territory, even on the assumption that distribution of the water powers could be made to all parts of the territory as required.

The important additional factor is to be noted that the "heating load," or consumption of solid fuel for purposes other than power, is approximately equal, in a populous, manufacturing territory, to the power load. In 1915 the U. S. consumed[6] 267,000,000 tons of coal for primary power and 275,000,000 tons for heating. This latter includes, besides domestic fuel, the large consumption for metallurgical purposes and gas.

Water power, therefore, in the United States will for a long time fall short of meeting the demands of industry for power and heat, certainly until methods are at hand for transmitting power very much longer distances than at present, and until the heating load becomes less of a factor in the power-heat demand.

A rapid increase in water power development, however, is taking place and will relieve in important degree the draft upon the coal resources, particularly as concentration of power production into large central distributing stations is brought to further accomplishment.

The Coal Reserve. With water power and petroleum playing no more than an auxiliary rôle, the principal part in the business of energy supply—both of power and heat—devolves upon coal. Director George Otis Smith of the U. S. Geological Survey[7] has estimated that there are available in the U. S. 2,500 billion tons of accessible coal, of usable quality, not including lignite. If consumption be continued at the present rate this should last 4,000 to 4,500 years, applied to both power and heat, and taking into account the lowering of the average quality due to increasing use of the large reserves of Western coal. Since, however, roughly three-fifths of this reserve of coal lies in the Western States where exists at present scarcely 5 per cent. of the demand for power and heat, the conditions in the Eastern States, as to the future coal supply, are less favorable. The coal of the Eastern and Central sections considered as a whole, may be estimated roughly to be capable of meeting the demands of those sections—at present rates—for 1,500 to 2,000 years; but the high-grade coals promise to be exhausted much earlier.

Anthracite and the easily-mined, thick seamed, low-sulphur coking coals have, it is variously estimated, a life of only 75 to 200 years.[8]

[6] P. Torchio, *loc. cit.*, p. 316.

[7] Geo. Otis Smith, "Industry's Supply of Energy," *Mechanical Engineering*, 43, 165 (1921).

[8] Geo. H. Ashley, State Geologist of Penna., in *Electrical World*, Nov. 22, 1919 (supplemented by private communication to the author), estimates the reserves

Conservation of Coal. Conservation of the coal resources will make most progress through an appeal to engineering efficiency and the advantages of the lowering of costs in industry. With rising prices of coal and cost of labor, the necessity for conservation in use becomes greater. That the important advances of recent years in the art of applying coal to industrial purposes have appreciable effect upon the rate of increase in consumption appears in the general trend of the curves for coal production in the United States shown in Figure 7.

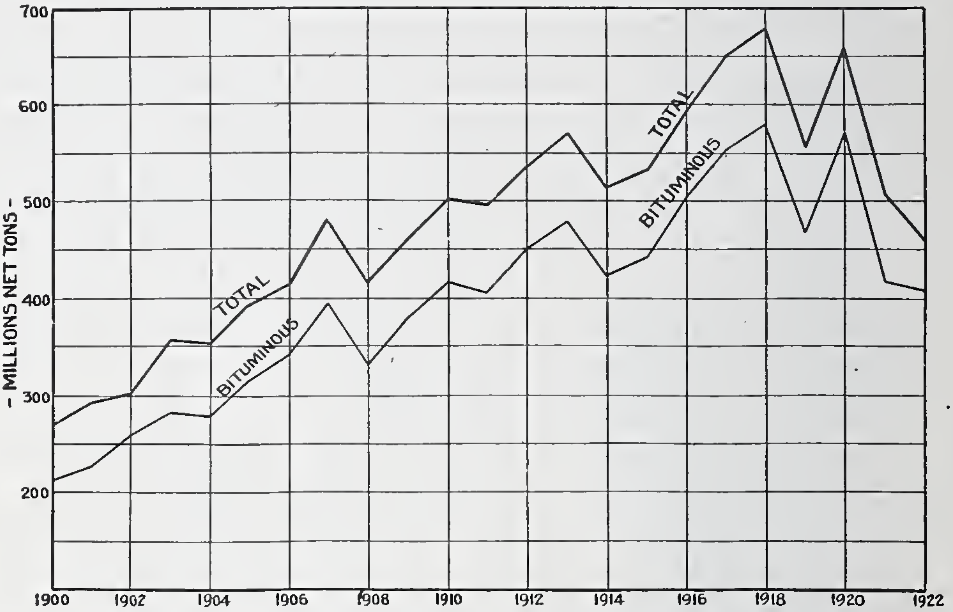

FIG. 7.—Growth of Coal Production in the United States (based on data of the U. S. Geological Survey).

It is evident that, making due allowance for the years of war-time activity—1916-18—for the inferior quality of much of the coal mined in that period under the urge of war necessities, and for the increased exports occurring in that period, the curve of coal consumption in the United States has since 1910 followed a much more gradual rise. It may be doubted, in fact, if the per capita coal consumption has since

of high-grade bituminous coal in Pennsylvania, in seams of 6 feet or more in thickness, as sufficient to last 80-85 years at present rate of increase in exhaustion.

M. R. Campbell, in Professional Paper 100-A, *U. S. Geological Survey,* p. 26, states: "Although by every reasonable estimate the ultimate exhaustion of the coal reserves of the United States appears to be an event so far in the future that it need concern this generation but slightly, the fact must be remembered that the bulk of the coal being mined today is the best in the country and that before long, perhaps within 50 years, much of the high-rank coal will be exhausted."

that year increased in a degree at all commensurate with the increase of industrialization and the betterment of the standards of living.[9]

Conservation of coal through improvement of methods of use has unquestionably accomplished much in lowering the rate of exhaustion of the high-grade coals of the Eastern section of the country. It is certain to make even more progress by this means in the future. Carbonization will find place in this progress, as outlined in later paragraphs—and its part will be of importance particularly in lessening the consumption of coal for the heating load, for domestic fuels, for the heating and reheating of metals and their reworking and for miscellaneous industrial heating needs to which the use of raw coal is poorly adapted and inefficient.

Some of the methods of coal conservation, arranged roughly in order of the extent of the savings likely to be secured are listed in the following:

1. Electrification of the steam railway lines, as far as is practicable.
2. Further development of water power and substitution thereof for part of the steam-generated power.
3. Centralization of power production in large distributing stations with increased average load factor, and economy of conversion of fuel to power.
4. Boiler plant economies through increased use of stokers, economizers, superheaters, feed-water purifiers, feed-water heaters, etc.
5. Elimination, in large part, of "non-recovery" or "bee-hive" coking of coal and replacement thereof by by-product coking with its direct saving equivalent to 25 to 30 per cent. of the coal.
6. Extension of the use of gas and powdered coal in metallurgical and other industrial heating processes, whereby a saving of 25 per cent. or more of the coal is secured.[10]

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[9] The following quotation in support of this view is taken from an editorial review of the coal industry in 1922, in *Coal Age* (C. E. Lesher, Editor), **23**, 83-4 (1923):

"Better utilization helps account for more results on less coal, . . . The railroads, for instance, made their coal do approximately 8 per cent. more work in ton-miles of freight handled in 1922 than in 1920, and about 3 per cent. more than in 1921. The revolution in coal utilization that has been going on for a number of years is concerned with the development of central-station plants. . . . Year by year they have been taking over the power load for industry. . . . The result is a gain in horse-power-hours with the same tonnage of coal, . . . Two years ago it was considered that 550,000,000 tons of bituminous coal represented a nominal requirement for the country. That figure is plainly 100,000,000 tons too high for the present. Consumption has contracted, relative to the power-producing and heat-requiring needs of the country. High prices and uncertainty of supply have driven consumers to substitution of oil, water-power, tar, and coke breeze, and the purchase of more economically produced central-station power."

[10] H. M. Thornton, *Journal of the Royal Society of Arts*, **68**, 346 (1920), cites specific data of savings accomplished in industrial heating furnaces of England by the use of gas.

W. C. L. Trinks, *Blast Furnace and Steel Plant*, **8**, 327 (1920) (also in "Industrial Furnaces," by the same author, Wiley & Sons, N. Y., 1923), demonstrates

7. The use of waste heat boilers applied to industrial heating operations.

8. Abatement of smoke and the inefficient burning of raw bituminous coal in homes, largely through increased use of gas and carbonized fuel. The direct saving in coal thereby is not likely to be large, but indirect benefits and recoveries will further conservation.

Geographical Aspects of Fuel Utilization in the United States. An instance of how carbonization is likely to enter as an economic factor of large importance in the utilization of fuels, appears in connection with the Western coals and the possiblity of rendering their immense resources practically useful. These coals and the lignites constitute well over three-fifths of the coal resource of this country. In the raw state most of these fuels have relatively a large content of water and a low heating value and slack badly in storage and by handling.

When the geographical center of industrial development shall have moved far enough to the West, toward the center of the fuel and power resource, as appears to be a natural sequence in the course of expansion of the power demand and of increasing scarcity and price of fuel in the East, then will arise the need of improved methods of utilizing these lower-grade coals. Among such methods will be processes of carbonization converting them into fuels of low moisture and high heating value.

Investigation of this problem by both the United States and Canadian Governments has led to the conclusion that carbonization methods in this connection are feasible and desirable.[11] Lignite has been converted in experimental units of commercial size into a carbonized fuel, suited to wide application for domestic and industrial purposes.

On the economic side the advantages of such development are stated by S. M. Darling of the Bureau of Mines,[12] as follows:

"Upwards of 2,000,000 tons of bituminous coal are shipped annually into that territory"—(Dakota and immediate vicinity)—"from Illinois, Indiana, West Virginia, Kentucky and Pennsylvania. The average haul of coal is 1,000 miles. If the Dakota lignite were put into stable and serviceable condition, by means of carbonizing and briquetting, this fuel demand could be supplied with an average haul of less than 400 miles. The average freight rate is about 4 mills per ton mile. Therefore, if the fuel and power requirements of this section were

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similarly for American conditions the economies to be secured in the reheating of iron and steel by use of gas or powdered coal.

[11] S. M. Darling, U. S. Bureau of Mines, Techn. Paper 178 (1918); E. J. Babcock and W. W. Odell, U. S. Bureau of Mines, Bulletin 221 (1923); O. P. Hood, *Mechanical Engineering,* May, 1923; W. W. Odell, U. S. Bureau of Mines, Report of Investigations No. 2441 (1923); Canadian Dept. Mines, Summary Report, 1921, No. 586; R. DeL. French, "Carbonization of Western Lignite" (Canadian), *Journal of the Society of Chemical Industry,* 41, 16-17 T (1922).

[12] Techn. Paper 178.

supplied from the Dakota lignite mines an annual saving would be effected of $4,800,000.00 in freight charges alone.

. . . .

"The economic waste involved in this almost transcontinental shipment of coal is little short of criminal.

"The above tonnage does not include the anthracite shipped into this Dakota territory, . . . amounting to about 1,500,000 tons annually."

Similar conclusions, modified as to detail, apply to most of the sections of the West where the lower grade bituminous and subbituminous coals as well as lignite abound. Constant experimentation is being carried on, even in the Central territory, as in Illinois,[13] to render the local coals, through carbonization or other improvement, better adapted, to efficient application in competition with those of the East.

Although the time of exhaustion of the Eastern coal reserve, and of a migration of the industrial center in any large degree westward by reason thereof, is probably remote enough to have little concern for the present generation, the trend in this direction is evident, and the need of adjusting fuel utilization methods with regard thereto cannot be denied.

Burning Coal "Raw"—as Opposed to Carbonization. The proposal, often made, that, in the interest of conservation, no bituminous coal should be directly burned, without preliminary recovery of byproducts through carbonization, is little more reasonable than to advocate that wood should never be placed on the fire without yielding first its quota of charcoal and wood-alcohol, or that grains and other foodstuffs should not be consumed until their starch and oils or the by-product alcohol, shall have been recovered for special uses.

Coal must needs be used as industry and civilization require, with as little expenditure as possible of the resource itself and of other assets, as labor and miscellaneous materials. It is likely to be carbonized, and properly should be carbonized—only to the extent that the economic demand for the special products thus derived creates prices that make the treatment profitable. There will not be a gain in fuel economy or any progress in conservation by carbonizing coal, if less of useful energy is obtained in the total of coke, gas, tar and light oil than can be made available from the raw coal itself directly applied. More coal, in that case, would have to be mined to yield the same ends.

Other products, as ammonia, add revenue, and may ensure a profit to the operation, but still no gain for conservation results if the energy usefully applied is less than in direct burning of raw coal. It happens, in favor of carbonization, that much of the actual prevailing practice in burning of raw coal, especially in small plants, is far below the possible maximum of efficiency, and in many cases could economically be replaced by the burning of gas. But it is not so in the case of the large well operated modern central stations.

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[13] S. W. Parr, *Gas Age Record,* 50, 531 (1922); also *Journal Industrial and Engineering Chemistry,* 13, 14-17 (1921).

As long as the products of carbonization are in sufficient public demand, by virtue of their superior qualities as fuels, to maintain adequate prices, carbonization remains a profitable operation. It cannot be expected to extend itself beyond the point where these favorable prices are to be had, nor, to offer beyond that, material help in coal conservation.

Raw coal, accordingly, as will appear from comparisons in later paragraphs, will be applied direct for many purposes—until conditions as to costs and losses incurred in the process of carbonization change materially.

Uses, in which Raw Coal is Advantageous. The power plant (see pages 50-52) finds that raw coal, when applied to steam raising by best modern methods, with use of the steam turbine, gives better efficiencies, greater conservation of the coal resource, and simpler and less costly operation, than the products of carbonization, produced either at low temperatures or high, coupled or not coupled with complete gasification of the coke. By-products do not alter the situation, unless portions of the coke and gas are so classed and are given over to special uses wherein they command high returns—above their ordinary fuel values.

The application furthermore of raw coal, in powdered form, for many purposes, the reheating of metals, the "burning" of Portland cement, etc., offers advantages in thermal efficiency, simplicity of plant, and costs, difficult to match by carbonization methods.

Uses in which Carbonization Proves Advantageous. It is therefore chiefly in certain limited fields, as in metallurgical processes, industrial heating operations, domestic heating and cooking,—fields realizing particular advantages from the use of these special forms of fuel, that the products of carbonization offer to the consumer adequate inducement to pay the costs of their manufacture.

The field thereby offered is large, possibly one-half or more of the total coal consumption, but it cannot reasonably, under conditions now at hand, be widened so as to encompass more than a small portion of the power producing field.

Gas applied to the reheating of metals for rolling, shaping, annealing and the many and various kinds of reworking, secures economies over coal—by virtue of labor saving, increased rate of output, improved product and reduced wastes. (See pages 76-7.) In the domestic fuel field, gas and coke or semi-coke are gaining ground rapidly in replacing coal, owing to the indirect advantages secured by smokelessness, convenience, labor-saving, and reliability. In meeting the heating load, as distinguished from the power load, carbonization finds its most successful application. The bulk of this heating load—at least two thirds of it—lies in the fields above named, i. e., in metal working and smelting and in domestic heating.

The Distribution of Energy. It is obviously an economic waste to transport coal as such—by railroad and truck—to the bins of the ultimate small consumer. There is haulage thereby of 20 per cent. of useless material in the shape of ash and moisture and at least an equal amount of combustible wasted through the lower thermal efficiency of the small consumer's plant. It is said[14] that one-third, approximately, of the railroads' ton-mile freight haulage is of coal.

The energy of coal may be distributed—from central plant to ultimate consumer,

(1) By electric current;
(2) By gas; or,
(3) By steam.

For power and light, method 1 provides unquestioned economies to the smaller consumer, and as concentration of power production into larger central plants is increased, with efficient long distance distribution of high-tension current, the costs are reduced and economies grow.

For distribution of energy for heating purposes, method 2, the piping of combustible gas to the ultimate consumer, is logically an improvement over distributing raw coal. One ton of coal at the gas plant can by modern methods deliver gas at the consumer's meter sufficient to do the work of 1.10 tons of coal in his furnace.[15] The 1.10 tons, furthermore, as used by the consumer cost him on the average 1.8 times what the 1 ton costs the gas manufacturer.

At the present time the gas manufacturer's conversion costs and particularly his distribution expense—due to costly piping systems and large expense of upkeep and attention—are more than enough to counterbalance the gain in coal cost above noted, and to put upon the consumer a cost for his improved fuel considerably higher than that of the equivalent coal. With advances, however even now at hand, in the lowering of both production costs and distribution costs, it will soon be possible to substitute economically the more logical and efficient fuel in households.

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[14] A. H. Armstrong (General Electric Co.), Report of Committee on Electrification of Railroads, National Electric Light Association (1920), pp. 16-17.

[15] By a combination of coke oven carbonization and conversion of the coke into water gas about 63-64 per cent of the thermal value of the coal can be put into the mixed gas thus made. By "complete gasification" processes 66 to 68 per cent. can be realized in the gas. In house heating by gas, it has been found ("Manufactured Gas for House-Heating," by Geo. S. Barrows and C. C. Winterstein, *Proceedings of American Gas Institute*, Vol. 11, 1916, part 2, pp. 908-956, especially p. 936; also Report on an Experiment in Residence Gas Heating at Denver, Colorado, by T. M. Foulk, American Gas Association, 1923, especially p. 9, column headed "Ratio of B.T.U. fired, gas to coal") that 30,000 cubic feet of 530 B.T.U. gas do the work of 1 ton of coal, or, in other words the requirement is 59 per cent. of the total heat in the gas making coal. Hence the gas making process delivers from 1 ton of coal 65/59 or 1.10 times the house heating power of 1 ton of average domestic coal, besides saving labor of handling and ash removal.

Conservation then will follow of 0.1 ton or more on each ton of coal required under old methods, as will also the logical saving in transport and handling above alluded to.

Gas will, more generally, be distributed from large central stations for long distances under high pressures. The modern welded mains—tight under 100 pounds pressure per square inch—make long distance transmission possible and marked economies in manufacture can be secured in the larger stations used to supply the larger territory.[16]

Transmission of heat by the medium of steam (method 3, above named)—as from central heating plants to individual consumers within a limited area—is costly, and is restricted, not only to small areas, but to small stations that have no better way of utilizing their exhaust steam.

Concentration of Power Development, "Super-Power" Stations. There can be no question of the trend in power development and distribution toward centralization. The large economies to be realized through increase of the load factor by correlation of the distributing systems, employment of large producing units with high relative efficiencies, reduction of the haulage of coal through placing of the stations near the mines and distributing electric current (at high tension) rather than coal,—all these gains are manifest. Much progress has been made already by the establishing of these large central stations in sections where conditions make the replacement of the older methods opportune.

It is safe to say that the average consumption of coal per unit of power output will continue for some time to decrease—owing to the gain in efficiency accomplished through this process of centralization.

Use of Carbonization Processes Impracticable for "Super-Power" Production. For these large central power stations preferably located near the coal mines, the use of carbonization schemes is often advocated, so as to permit the saving of by-products. It is a difficult matter, however, under present conditions to make such schemes economically practicable. The by-products are saved, to be sure, but at such cost that the prices usually to be obtained for them will not justify it.

The reduced thermal efficiencies attained in carbonization and the costs of carbonization render this method, as has been pointed out in previous paragraphs, an expensive one for power production.

Additional drawbacks appear in the relatively great capital investment required, the complexity of plant and large employment of labor, and especially in the much larger quantity of coal required to be handled and transported.

The most promising field in which investigations are being prosecuted in this line is that of carbonization at low or medium temperatures accompanied by gasification of the coked residue in such manner as to give large yield of ammonia. With this latter asset and that of an important yield of tar oils (applicable in producing substitutes for petroleum), the net cost of power obtained through burning of the gas (or partly by use of gas engines) is materially reduced—possibly to a level near that of the direct burning of raw coal accompanied by use of steam turbines. There is a possibility also of augmenting the "by-product" revenues by making some part of the coked residue into a domestic fuel, marketable as an anthracite substitute at favorable prices. Such an operation would be more than a power station. It would constitute a central fuel and power depot, and manufactory for certain by-products. The scale of the operation, and of the transport and handling of coal and products, would be a greatly expanded one as compared to that of power production alone, and this in itself, by adding to the risks, necessitates a larger margin of safety in promised returns.

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[16] See references, p. 79.

British Conclusions on Power Production With By-Product Recovery. The British Ministry of Munitions of War, through its Nitrogen Products Committee, made, during the World War and after, a thorough investigation of the various possible means of large-scale power production, open to their use for nitrogen fixation from the air on a large scale. Their conclusions are presented in detail in the Final Report of the Nitrogen Products Committee (published by His Majesty's Stationery Office, London, 1920). On the subject of by-product recovery schemes the following conclusions from the Report are pertinently to be quoted here.

(Paragraph 133, page 30): "There is no question that the direct use of coal under boilers in conjunction with steam turbo-electric units of large size necessitates the smallest capital outlay and the smallest consumption of coal for a given output of power in kilowatt years. With such a plant, however, nitrogenous and other by-products from the coal are entirely lost, and when the potential value of these by-products is taken into account, it does not necessarily follow that direct coal-firing is the cheapest method of obtaining power from coal."

(Paragraph 431, page 85): "It has long been recognized that the prosperity of industrial countries is essentially dependent upon the utilisation of their fuel resources to the maximum advantage, and solutions of the question are being sought in various directions. In general, the most promise is held out by methods involving the treatment of fuel with by-product recovery, and the introduction and extensive development of such methods would lead to a notable increase in the production of ammonium sulphate."

(Paragraph 636, page 127): (a) "As compared with direct coal-firing, all by-product power schemes involve a larger consumption of coal, a larger capital outlay and higher operating costs for a given output of power in kw-years." (b) "In the present state of knowledge, the application of by-product recovery processes to power production on a large scale offers no *immediate* prospect of reducing the cost of electrical energy from coal below the figure attainable by direct coal-firing and the use of large steam turbo-electric units. Moreover, the employment of any of the *well-established* methods of treating coal for by-product recovery, namely, high temperature carbonisation (gasworks practice or coke-oven practice) or the complete gasification of coal in existing types of recovery producers, offers little or no prospect of competing upon a commercial basis with direct coal-firing." (g & h) "High prices for coal and high rates of wages are a handicap to all by-product power schemes, owing to the thermal losses in such processes and the consequent increase in the quantities of coal required to be treated to obtain a given output of power. Moreover, a sustained market price for by-products is an essential factor in any margin in the cost of generation as between by-product power stations and coal-fired stations. The financial stability of by-product power schemes, confronted with fluctuations both in the cost of coal and also in the market price of some or all of the by-products, would be much less certain over a period of years than that of direct firing."

(Paragraph 637, page 128): (a) "In the present state of the art, the employment of gas-engines for the production of power upon a scale sufficient for the economical operation of nitrogen fixation processes under British conditions cannot be regarded as practicable."

Detailed data, from the Report (1920) of the (British) Nitrogen Products Committee, relating to the costs of power by methods involving carbonization are presented in the footnote.[17]

Adaptation of the British Conclusions on By-Product Recovery Power Production to American Conditions. The conclusion that the combination process, comprising low temperature carbonization and gasification of the resulting coke in recovery producers, offers the best present prospect among by-product recovery power

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[17] *British Estimates Upon a Proposed Power Plant Using a Combination Process, Low-Temperature Carbonization Followed by Gasification of the Resulting Coke in Recovery Producers.* (Using "System B," the low-temperature carbonization process offering most favorable results, by the claims of its proponents.)

Note: This combination process, among all those by-product recovery power schemes studied by the British Committee, yields, according to the Committee's estimates, the most favorable over-all net power cost. The yields of gas and by-products, and the operating costs, are taken in accordance with the claims for the process, not yet substantiated in commercial trial.

(The following tabulated data are—Tables 2a to 4—from Final Report of British Nitrogen Products Committee, 1920, pp. 176 and 190-195.)

Table 2a.

Low Temperature Carbonization:
Yield of Products (Claimed) per Ton (2,240 Pounds) of Coal (System B).

Low temperature coke and breeze	1,400	pounds
Stripped gas (of 700 B.t.u.)	7,500	cubic feet
Ammonium sulphate	28	pounds
Tar	18	gallons
Benzols	4.5	gallons

schemes, for reducing the cost of power below that of direct coal firing, is probably justified also for American conditions. Although in America, as compared to England, high temperature carbonization

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Table 2b.

Thermal Balance Sheet (Claimed) for Low Temperature Carbonization (System B.)

	B.t.u. per Ton of Coal Carbonized	
Thermal value of original coal (as fired)	26,880,000	
Thermal value (net) of products:		
Stripped gas, 7,500 cubic feet at 700 B.t.u. (net) per cubic foot..........	5,250,000	
Low temperature coke, 0.7 ton at 11,500 B.t.u. per lb......................	18,030,000	
	23,280,000	
Plant requirements:		
Coke or gas for heating retorts, expressed in B.t.u....................	2,800,000	
Balance available for power production..	20,480,000	
Thermal efficiency of carbonization plant		76.2 per cent.

Table 2c.

Probable Yield in Gasification Stage.

	Per Ton of Coal
Percentage yield of coke and breeze..........	70 per cent
Ammonium sulphate, 92 × .70................	64.4 pounds
Power gas (130 B.t.u. per cubic foot) 140,000 × .70	98,000 cubic feet
Total B.t.u. in gas..........................	12,740,000

Table 2d.

Probable Total Yields, Combined Carbonization and Gasification Processes.

Ammonium Sulphate:	
Carbonization	28.0 pounds
Gasification	64.4 "
Total	92.4 pounds
Tar	18.0 gallons
Benzols	4.5 gallons
Power gas:	
Carbonization (700 B.t.u.).................	7,500 cubic feet
Gasification (130 B.t.u.)..................	98,000 " "
Total (av. B.t.u. 170)....................	105,500 cubic feet
Total B.t.u. in gas..........................	17,990,000

Table 2e.

Thermal Requirements of Producer Plant. (Thermal Efficiency of Main Gas-fired Boilers taken at 75 per cent.)

B.t.u. required per pound of coke gasified...........	1,378
" " for total coke obtained from 1 ton of coal, 0.7 × 2,240 × 1,378	2,160,000

in coke ovens offers better returns from by-products than it does in Britain, and a larger rate of output of all products per year, the plant

Table 2f.

Thermal Balance Sheet for Combination Process.

		B.t.u. per Ton of Coal Utilized
Original coal as fired		26,880,000
Thermal value (net) of gas, from carbonizing and producing stages		17,990,000
Plant requirements:		
Carbonizing section	2,800,000	
Producer section (with steam taken from turbines, assuming boiler efficiency of 75 per cent.)	2,160,000	
Total		4,960,000
Balance available for power production		13,030,000
Combined thermal efficiency		48.5 per cent.

Table 3a.

Capital Outlay for Power Installation Comprising Carbonizing Plant and Recovery Producers (on scale of 100,000 KW maximum demand).

Total fuel to be treated per KW-year of 8,760 hours (compare coal-fired station, 6.5 tons) .... 14.3 tons

Capital cost (per KW of maximum load):

		Pounds Sterling
Carbonizing section, 14.3 × .788	11.27	
Producer section (excluding steam-raising plant) 10.0 tons fuel at .69	6.90	
Steam-raising plant (16 per cent. of main boiler plant)	0.36	
Total		18.53
Power section		10.20
Total capital cost per KW of maximum load		28.79

Table 3b.

Operation Costs of Power Installation. Comprising Low Temperature Carbonization Plant and Recovery Producers for Gasifying the Coke. (Scale 100,000 KW maximum demand.)

Total fuel to be treated per KW-year of 8,760 hours:

Coal to be carbonized		14.3 tons
Coke, resulting, to be gasified		10.0 tons
Operating costs (per full KW-year):		Pounds Sterling
Carbonizing section 14.3 at 2.75s.	1.97	
Recovery producers 10.0 at 3.25s.	1.02	
Capital charges at 10 per cent.	1.85	
Total		5.44
Power section (including capital charges)		1.45
Total operating costs per KW-year (exclusive of cost of coal)		6.89

cost and operating cost in America per ton of coal carbonized, is higher than the British figure used above. This difference will probably counterbalance financially the gains in the former respects, and therefore it cannot be expected that the usual system of coke oven carbonization will secure in America materially better results—*for power production* (relative to other processes)—than in England. (See also Figure 8, page 51.)

For low temperature carbonization no process has, thus far, been successfully worked out in America on a commercial scale. It is possible, however, to assume certain yields and costs as claimed by the proponents of processes under trial, as far as they do not exceed reasonable probabilities, and base thereon an optimum deduction of the cost of power by use of such process.[18]

Table 4.

Summary (from British Report). *Cost of Electrical Energy via Low Temperature Carbonization followed by the Gasification of the Resulting Coke in Recovery Producers.* (Coal taken at 10s per ton —2,240 pounds—and the net revenue from the sale of ammonium sulphate at 10 pounds sterling per ton). Scale, 100,000 KW maximum demand. (Efficiency of gas firing taken at 75 per cent.)

Debit:	Pounds Sterling	
Total working costs and capital charges	6.89	
Coal cost, 14.3 tons at 10s	7.15	
Total		14.04
Credit (net revenue):		
Tar, 18 gallons per ton at 3d. per gallon	3.22	
Benzol, 4.5 gallons per ton at 8d. per gallon	2.14	
Ammonium sulphate, 92.4 pounds per ton at 1.07d.	5.90	
Total credits		11.26
Net cost per KW-year (pounds sterling) (about $13.52)		2.78

Compare net cost of same by direct coal firing with coal at 10s. (about $2.43) —pounds 4.70 (about $22.85).

Note: With cost of coal at 15s. (about $3.65), the cost of power by the combination by-product recovery process becomes equal to that by direct coal firing, viz., 6.4 pounds sterling (about $31.14) per KW-year of 8,760 hours, and for coal prices exceeding 15s. ($3.65) the cost of power increases more rapidly by the by-product recovery process than by direct firing, assuming net revenue per ton of ammonium sulphate at 10 pounds sterling. When sulphate is at 12 pounds (about $58.40) per ton, the curves of power costs by the two methods, with increasing coal cost, cross at 18s. (about $4.38) per ton. (See Chart 8, facing p. 195, British Nitrogen Products Committee, Final Report.) In other words, at that price of coal and of ammonia the net cost of power by the two systems becomes the same.

[18] It is important to note here that the British "System B" on which the quoted data are based, claims obviously impracticable yields, as illustrated by the thermal balance sheet, Table 2b. This sheet indicates that yields of coke and gas are claimed aggregating a B.t.u. value of 23,280,000 on a ton of coal of 26,880,000 B.t.u., and in addition thereto 18 gallons of tar and 4.5 gallons of benzol. The former at 17,000 B.t.u. and the latter at 18,000 B.t.u. per pound

For American conditions—in the absence of industrial operating data, we may use certain assumptions for the sake of argument, based upon the claims[19] for processes tried out on an experimental scale.

The following scheme is so drawn as to give maximum returns in by-products, ammonia, oils and enriching gas:

Trial Scheme for Power Production with By-Product Recovery, Using Low Temperature Carbonization—Under American Conditions.
(Draft of possibilities based on claims not yet substantiated.)

Capacity of power plant, 100,000 KW, maximum demand. Thermal efficiency, from coal to available B.t.u. in gas for boiler firing, 44.0 per cent. Coal required, 20.0 net tons per KW-year (100/44 or 2.3 times that required for direct coal firing), per day 5,500 net tons.

TABLE 5A.

LOW TEMPERATURE CARBONIZATION (First Stage).

	Yields per 2,000 pounds of coal, of 27,000,000 B.t.u.	
Total coke (74 per cent.)	1,480 pounds	19,200,000 B.t.u.
Gas—of 800 B.t.u.	3,000 cubic feet	2,400,000
Tar	20 gallons	3,100,000
Light oil	5 "	800,000
		25,500,000 B.t.u.
Used for carbonizing purposes, through medium of producer gas at 80 per cent. efficiency		2,000,000
Net B.t.u. in products (87.0 per cent.)		23,500,000

Note: Rich gas from carbonization to be sold for enrichment purposes yielding higher return than for steam raising on plant.

Tar and light oil to be sold.

GASIFICATION (Second Stage) IN AMMONIA-RECOVERY PRODUCERS.

Net coke B.t.u. available for manufacture of producer gas (19,200,000 less 2,000,000)	17,200,000
Available B.t.u. in producer gas (80 per cent.)	13,800,000
Deduct B.t.u. for steam used in producers	2,000,000
Net B.t.u. available in gas for boiler-firing	11,800,000
Net thermal efficiency, coal to available gas	43.7 per cent.
Ammonium Sulphate Yield—per ton coal	65 pounds

(6 pounds from first stage, plus .74 × 80 = 59 pounds from second stage.)

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would add a total of 3,100,000 B.t.u. to the returns above named from coke and gas, making a grand total for the thermal value of products—claimed—equal to 26,380,000 or 98 per cent. of that in the coal. Measurements made in actual practice—e. g., those of the British Fuel Research Board—on low temperature carbonization (Report, 1922, of the Fuel Research Board, Dept. of Scientific and Industrial Research, for 1920-21, second section, p. 51, table 5), show a thermal loss ranging from 4.5 per cent. to 7.9 per cent. It appears probable that the yield of 7,500 cubic feet of gas of 700 B.t.u., accompanied by a yield of 18 gallons of tar and 4.5 gallons of benzol, is impracticable in average operation.

[19] R. D. Lamie, *Coal Age,* **24**, 171 (1923), and V. Z. Caracristi, *Power,* May 29, 1923 (on Piron Process); H. A. Curtis, *Chem. & Met. Engineering,* **28**, 118 and 171 (1923) (Carbo-coal Process).

TABLE 5B.

CAPITAL OUTLAY AND OPERATING COST.

Impossible even to approximate closely, owing to lack of operating experience which would show capacities, labor requirements, etc., but estimated roughly on the basis of claim for processes as follows:

	Per Full KW-Year
Carbonizing Section: *	
Capital charge, at 18 per cent., at $0.90 per ton of coal carbonized per year, 20 times $0.90	$18.00
Operating cost, 20 times $1.10	22.00
Gasification Section: *	
Capital charge, 14.8 tons at $0.65	9.62
Operating cost, 14.8 tons at $1.00	14.80
Power Section: † (exclusive of coal cost)	18.00
Total capital charge and operating cost	$82.42

* Lower estimates than these for the costs of carbonization and gasification are and will be made, undoubtedly, by advocates of several processes now under experimentation. Until these processes, however, shall have demonstrated their costs over a reasonably long period of commercial operation, and shown an ability to improve upon the records thus far made, it would appear unsafe to use lower cost figures than those given above in estimating the returns from average continuous operation.

† This estimate of power plant cost (fixed charges and operating, exclusive of coal) is placed somewhat lower tran that of the U. S. super-power investigation (*U. S. Geological Survey*, Professional Paper 123, 1921, pp. 186-188), whose estimate on a 120,000-kw. plant is about $18.00 for fixed charges and $4.50 to $5.00 for operating, under prices of labor and materials prevailing in 1919.

The estimate made above takes into account the apportionment of part of the usual power plant cost (such as land, coal handling, etc.) to other sections of the combination plant.

TABLE 6.

SUMMARY. COST ESTIMATE OF ELECTRICAL ENERGY VIA LOW TEMPERATURE CARBONIZATION FOLLOWED BY GASIFICATION OF THE RESULTING COKE IN RECOVERY PRODUCERS (under American Conditions).

(Coal taken at $4.00 per net ton, net return from ammonium sulphate—less cost of acid—assumed at 2.5 cents, rich gas assumed as sold for enrichment of city gas at 8 cents per 100,000 B.t.u., tar sold for fractionation into light and heavy motor fuels, creosote oil, etc., at 6 cents per gallon, light oil sold for motor fuel at 15 cents.)

		Per Full KW-Year
Debits:		
Coal, 20 net tons at $4.00	$80.00	
Total operating costs and capital charges (see above)	82.42	$162.42
Credits:		
Rich gas, 20 times 2,400,000 B.t.u. at 8 cents per 100,000	38.40	
Tar, 20 × 20 gallons at 6 cents	24.00	
Benzol, 20 × 5 gallons at 15 cents	15.00	
Ammonium sulphate, 20 × 65 pounds at 2.5 cents	32.50	109.90
Net cost, per KW-year of 8,760 hours		$ 52.52

Note. Changes in market conditions favorably influencing disposal of the rich gas or tar, and raising even slightly the prices obtained, would have a large effect in lowering the cost of power.

On the other hand, owing to the large plant investment and great value of the products handled, any degree of depression affecting the load factor on the plant or the market for products, would have relatively a tremendous effect in raising the cost of power.

The coal required for this scheme of power production is at least 2.3 times that for direct coal firing; the aggregate value of materials to be handled—coal and products (exclusive of power), is about 6 times that necessary for direct coal-firing.

Use of High Temperature Carbonization (as in coke ovens) **for Power Production.** In previous paragraphs attention has been called to the high costs and energy losses which make this method of power production impractical, as compared to direct coal firing. The Final Report of the British Nitrogen Products Committee may again be referred to here (see Chart 3, therein, page 174) to show their finding, that by the firing of coke and gas under the boilers (both at 75 per cent. efficiency) and crediting sales of tar, benzols, and ammonium sulphate, (the latter at the equivalent of 2.6 cents net per pound, with coal delivered at 16.5s or $4.00 per gross ton, the net cost of power per full KW-year is 8.65 pounds sterling or $42.04. At the same price of coal, the cost of one full KW-year by direct coal firing is given as 6.85 pounds sterling or $33.29.

In Figure 8 is shown graphically the loss incurred in applying coke oven carbonization to steam power production, under American conditions. This figure is devised to indicate the recovery of values from $1.00 of outlay in coal and production costs (including capital charge). Power generating costs are not taken into consideration, but only the yield of available fuel value in coke and gas as compared to coal. The loss is indicated as 22 per cent. of the outlay.

Estimated Relative Cost of Power (in U. S.) by Direct Coal Firing. The estimate by the super-power investigation, of the *U. S. Geological Survey,* (Professional Paper 123, p. 187) of the total production cost of power, in a direct-fired, steam turbine plant of 300,000 KW capacity, using bituminous coal at $5.30 per net ton in bunkers, is $45.10 per KW-year at 80 per cent. capacity. When projected to 100 per cent. capacity this becomes $51.80, and when modified to the basis of $4.00 per ton of coal (to conform to that of the estimate on the combination plant), the cost per full KW-year becomes $44.70.

This estimate of unit cost, being figured on a plant of 300,000 KW capacity, would be increased somewhat when adjusted to one of 100,000 KW; a rough estimate based on data used by the super-power commission (*loc. cit.*) would add $1.50 for capital charge and $3.00 for coal, which places the total cost per full KW-year on a 100,000 KW plant, at $49.20.

General Conclusions on Relative Costs of Power. The above estimated cost, $49.20, by direct coal firing is lower than that estimated on page 49, $52.52, for the combination by-product recovery plant, using low temperature carbonization followed by gasification of the coke with ammonia recovery.

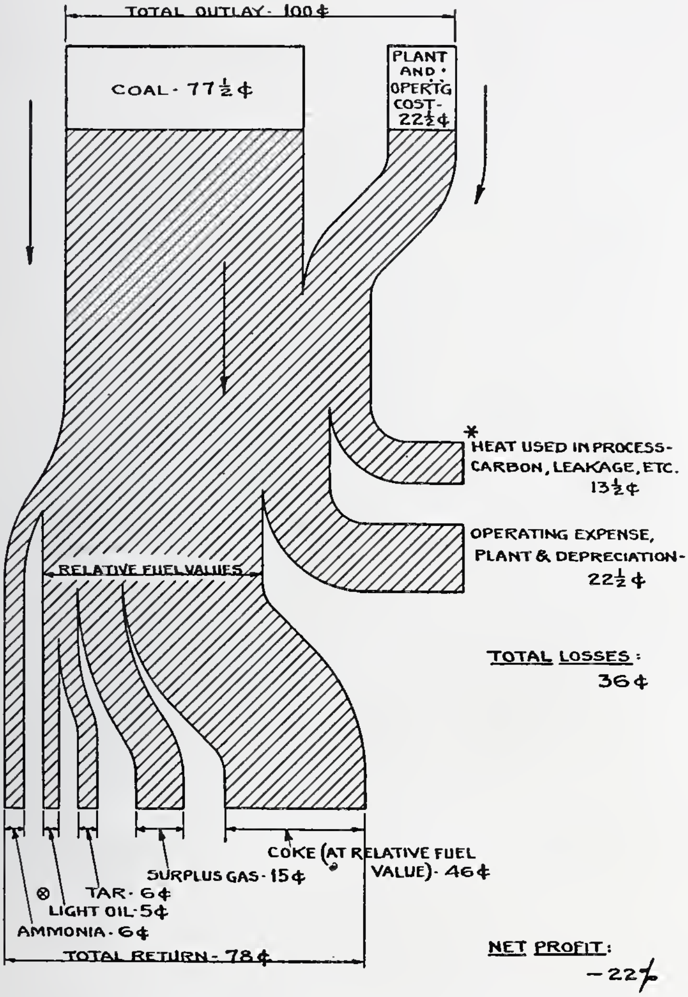
TOTAL OUTLAY · 100¢
COAL · 77½¢
PLANT AND · OPER'T'G COST · 22½¢
* HEAT USED IN PROCESS-CARBON, LEAKAGE, ETC. 13½¢
OPERATING EXPENSE, PLANT & DEPRECIATION - 22½¢
TOTAL LOSSES: 36¢
RELATIVE FUEL VALUES
COKE (AT RELATIVE FUEL VALUE) · 46¢
SURPLUS GAS · 15¢
⊗
TAR · 6¢
LIGHT OIL · 5¢
AMMONIA · 6¢
TOTAL RETURN · 78¢
NET PROFIT: −22%

Fig. 8.—Average Commercial Returns in Coal Carbonization, when applied as an auxiliary in steam power production.

An all-important phase, furthermore, of the comparison of these costs, is the fact that they are made on the basis of assumed 100 per cent. load in both cases. When the load factor is reduced, as would be necessary in practice, the unit costs by the combination by-product recovery scheme increase much more rapidly than do those in the direct coal fired plant, owing to the much higher capital investment in the former and the greater amount of labor used in operation.

It is fully evident, therefore, from Table 6 that, under conditions as to costs, prices and yields prevailing in American practice, or likely to prevail in the near future, the processes of low temperature carbonization and of gasification which are at hand do not, as yet, offer *for application in power production,* the commercial inducement necessary for large capital investment.

Development and improvement of processes, however, is going on, and may change the situation rapidly. The use of the cheaper grades of coal, the employment of oxygen-air mixtures for gasification, the improvement of capacity or the rate of output per unit in the low temperature carbonizing operation,—these possible developments, together with the growth of markets for ammonia and the oils of low temperature carbonization, may in the near future bring these processes into a competing relationship with the direct coal-burning system. It will be difficult, however, to offset, by the gain in by-products and the conservation of ammonia and oils, the serious drawback of larger coal handling and transporting operations, and the increased complexity of the business undertaking involved.

Potential Developments in Fuel Utilization. It may be set down as highly probable, on the basis of the conclusions just arrived at, that coal carbonization and by-product recovery methods will not be used in the immediate future for steam power production. Outside of the field of power production, however, it is possible to foresee increasing application of coal carbonization in some or all of the following lines.

(1) *Gradual displacement of the burning of raw coal in homes by the use of gas.* This will be accomplished when gas of 350 to 450 B.t.u. per cubic foot (instead of the present average of 550 B.t.u.) is authorized for public distribution, enabling manufacturers to reduce production costs materially, through increase of thermal efficiency in manufacture; and when distribution costs (now disproportionately heavy) are lowered by systematizing delivery in trunk lines at high pressures over long distances with low pressure substations for final distribution. Aid may perhaps be had from the city or state looking toward the lowering of investment charges on public distribution systems.

The use of existing natural gas pipe line systems is likely to be advantageous for this purpose in some localities.

(2) *Increasing use of gas and tar-oils or raw tar in industrial heating furnaces.* This growth is now under way and will be more rapid when the cost reductions outlined in the preceding paragraph shall have been accomplished and the improvement in distribution, using a system of separate trunk lines serving industrial districts.

(3) *Development of low temperature carbonization—largely for increasing the supply of fuel oil and motor fuel.* The development is likely to be accomplished chiefly through methods of increasing the capacity of the operation per unit cost of investment. Yields of 20-25 gallons of oil per ton of coal are not improbable by this method. When

ultimately a large carbonization industry, by this process, is established, say possibly to the extent of one-third of all the coal applied to the heating load, there could be produced thus two billions of gallons per year of this oil, or about 10 per cent. of the 1922 crude petroleum consumption.

The gas from low temperature carbonization, being rich in heating value and composed of permanent gases which do not cause losses by condensation, will be found especially well adapted for use in enrichment of low-cost, low B.t.u. gas for public distribution.

(4) *Large combination central stations* may in the future be found advantageous, producing gas for wide distribution at high pressure, semi-coke for certain domestic and special uses, and oil and ammonia as by-products. Saving in railroad haulage of coal would be instituted by such an arrangement.

Chapter 3.

The Industrial Systems of Coal Carbonization.

The systems by which coal carbonization now is applied industrially are, in the order of their importance (by tonnage used) as follows:

1. By-product coking,
2. Bee-hive coking,
3. Gas making in horizontal retorts,[1]
4. Gas making in vertical retorts (intermittent and continuous),
5. Low temperature carbonization.

General Comparisons. The systems of coal carbonization differ widely among themselves in the size of carbonizing chamber used and in the cost of plant investment per unit of producing capacity. The physical conditions within the retort or oven also are very different, (see pages 55-6, 59-60).

Development of the systems has been along different lines, since different objects, in the earlier stages, were in view.

The early gas retorts, horizontal, and using a small thin charge (300-500 pounds) of coal, were designed to make lighting gas, a maximum yield of candle power and volume. Larger gas retorts then appeared, some of them changed from the horizontal to the vertical position, and had as their principal objects the lessening of the labor of operation, the increase of unit capacity so as to lower costs, and the betterment of coke and by-products—the luminosity of gas being relegated in some degree to secondary position. Coke ovens, now frequently of a size to hold 15-16 tons of coal, were developed primarily for making coke, with little design at first of their adaptation to gas manufacture.

Comparisons are shown graphically in Figure 9. The relationships indicated are based on average dimensions, operating capacities, and costs. The latter are expressed in relative figures only, as between the various systems, since absolute costs and values are so variable from year to year, that any estimate made now would be obsolete before there should be time to use it. The investment cost per unit of capacity is affected in important measure by the size of the installation, and accordingly for comparisons like that of Figure 9, a certain size of plant must be assumed. For other sizes the relationships are in some respects materially altered.

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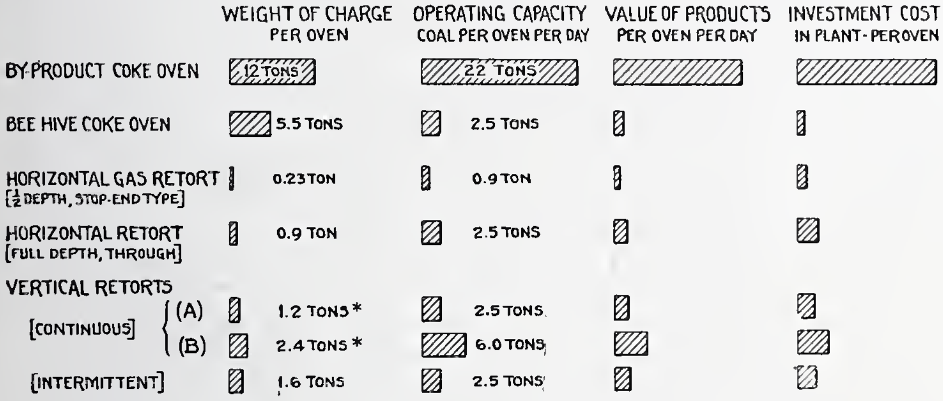
[1] It is likely that the respective ranks of horizontal retort gas and vertical retort gas, in tonnage of material used, will, in a short time, be the reverse of that shown above.

The Coke Oven and the Gas Retort. By the evolution of the carbonization unit from the 500 pound retort to the 12-ton coke oven, or even to the one-ton vertical, a marked reduction in the amount of handling of materials has been secured, and an improvement in quality of coke and by-products. But for the plant of variable load, the large units are not as well able to adjust themselves to a reduced demand, and generally they put upon the operation, when the load is variable, a higher fixed charge and "overhead" expense per unit.

"Bulk" carbonization, as in coke ovens, wherein relatively large units or charges are carbonized, presents, in comparison with the gas-retort system using small thin charges, an important difference in the speed of carbonization and in the rate of gas production from a given quantity of coal. For instance a 12-ton charge of coal in the modern by-product oven is coked in 16 hours and produces as an average, 8,000 cubic feet of gas per hour, while the same quantity of coal charged into 8 benches of 6's of horizontal gas retorts, each taking a 500-pound charge, is carbonized in 6 hours and produces 22,000 cubic feet of gas per hour.



* In this case, holding capacity.

FIG. 9.—Comparison of Types of Carbonizing Systems.

Carbonization by the gas retort system is therefore a more rapid, if more destructive and more costly, method of coal distillation than the coke oven system. The latter in turn is more rapid (and more destructive) than the "low-temperature" systems.

The yields per ton in the two former cases do not differ greatly, nor the tonnage of coal carbonized per day for a given gas output. But the retorts are charged 4 times in a day and the coke ovens but 1.7 times. The former give flexibility in control of output, the latter, greatly reduced labor of charging and discharging and of handling of coal and coke, better coke and better by-products.

Bee-Hive and By-Product Coking. Description of these processes in detail is reserved for another chapter. A comparison of the two, however, in their broad aspects, and a consideration of their progress and prospects is in order at this point.

Bee-hive coke making is the old and primitive method of securing coke for metallurgical purposes. By-products are neglected. The process is slow and wasteful—not only of the by-products but of the coke—for 6 to 10 per cent. of the latter is burned (together with the volatile matter) to give heat for the carbonization. The volatile products are allowed to burn in the top of the "bee-hive," throwing their heat down onto the layer of coal (23-26 inches) lying on the bottom. The heat penetrates slowly, in the one direction—downward—and produces an excellent hard strong coke in long pieces.

The coking of a 24-inch layer requires in the bee-hive oven 48 hours, and uses the heat of *all* the gas, tars and oils with one-twelfth of that of the coke. In the by-product oven the coal charge is coked from both sides toward the center—producing thus shorter and blockier pieces than in the bee-hive. The coking is rapid—by comparison—16 inches in 16-18 hours—or at twice the rate of the bee-hive. No burning takes place within the oven—the heat being supplied from flues alongside—to which about 40 per cent. of the oven gas after being stripped of by-products is returned and burned.

The yields and recoveries are very much better in the by-product oven. Its thermal efficiency is 85 to 87 per cent., while that of the bee-hive oven is 60 per cent. (unless the heat of the waste gases is recovered by waste heat boilers, when the efficiency may be raised to 75 to 80 per cent.). The commercial value of the products is usually 1.5 to 1.6 times that of the coal, while in bee-hive coking it is 1.10 to 1.15.

Yet, bee-hive coking chiefly by reason of its simplicity and low cost, finds favor and has been retained in an important degree, both in England and America, as a process of metallurgical coke manufacture. For many years, and until very recently, it produced annually more coke in America than the by-product process. Figure 10 shows the growth of production by the two methods. In spite of its waste of the material resource, and of potential by-products in large measure, it has the advantage, sometimes of transcending importance (when good coking coal is cheap and plentiful), of requiring the investment of relatively little capital.[2]

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[2] The following is quoted from Mineral Resources of the United States, *U. S. Geological Survey,* 1920, part 2, chapter 34, Coke and By-Products in 1919-1920, by R. S. McBride, p. 376:

"A by-product coke-oven plant requires an elaborate organization and a large investment per unit of coke produced per day. Operators of such plants cannot afford to close them down and start them up with every minor change in market conditions. It is not altogether a question whether bee-hive coke or by-product coke can be produced at a lower price at any particular time. Often by-product coke will be produced and sold at less than cost simply in order to maintain an organization and give some measure of financial return upon the large invest-

This advantage becomes large when depression of the coke market, in periods of inactivity of the coke consuming industries, causes a slowing-down of the coke making plants, with consequent heavy losses in investment charges in those whose cost of installation is high. It is a question of the balance between losses thus incurred by one system in certain periods, and the losses of coal and by-products incurred by the other during all periods of its operation.

The result of this relationship is likely to be a permanent retention of the bee-hive oven, in America, to the extent necessary to "take up the slack" in times of depression, to relieve, in other words, the costly by-product oven plants in those times, from serious strain due to reduced rate of output and increased overhead expense. To do this, the bee-hive ovens would operate only to meet the high peaks of the varying load.

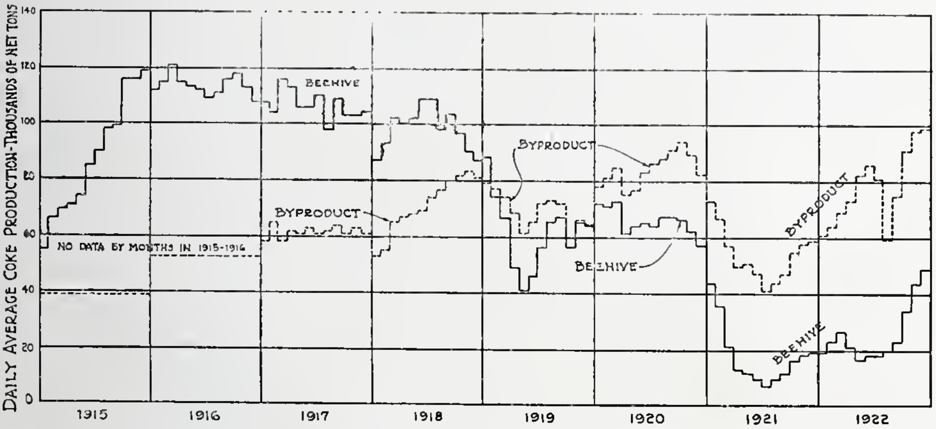

FIG. 10.—Growth of Bee-hive and By-Product Coke Production in the United States (diagram by U. S. Geological Survey, R. S. McBride).

A comparative statement of costs and financial returns by the two processes, assuming certain installation costs and values of products only for the purpose of correlation, is presented in Table 7. Absolute costs vary widely from time to time and from place to place, and cannot be deduced correctly from the figures here given. The financial advantage of the non-recovery coking process is apparent for periods in which a sustained and favorable market for by-products is, even temporarily, absent.

The estimates in Table 7 are based on an assumed operation at 90

ment, which would otherwise remain entirely unproductive. As a natural consequence of this relationship of investments in the two types of plants, it may be expected that in the future most of the fluctuations in production will occur in the bee-hive branch of the industry. In other words, the bee-hive ovens will serve the purpose of stand-by equipment and the by-product ovens will be the normal operating agents in the supply of metallurgical fuel."

TABLE 7.

Bee-hive and By-Product Coking—Comparison of Costs With and Without By-Product Recovery.

Cost of 1 ton of furnace coke, (A) made in bee-hive ovens at the mines, and (B) made in by-product ovens located in or near a city (on the Atlantic seaboard) for favorable disposal of gas and by-products.

		A Bee-hive		B By-Product
Costs:				
Coal: 1.667 tons in bee-hive ovens, at $2.50		$4.17		
1.500 tons in by-product ovens, at $5.00 (including freight)				$ 7.50
Investment Charge: on bee-hive ovens, 20 per cent. of $2.75 (the capital per ton of coke per year)		.55		
On by-product ovens, 16 per cent. of $6.50				1.04
Operating Expense		.66		1.87
Freight on Coke (to market at locality of by-product plant)		3.00		
Total cost, not crediting by-products		$8.38		$10.41
Credit from by-products:				
Coke breeze at $2.00 per ton	$ .08		$ .16	
Ammonium sulphate, at $50.00 per ton	..		.90	
Tar, at $0.04 per gallon	..		.60	
Benzols, at $0.15 per gallon	..		.56	
Surplus gas, at $0.10 per 1,000	..		.90	
		$ .08		$3.12
Net cost, one ton of coke, after crediting by-products		$8.30		$7.29

per cent. of full capacity, in other words at the rate found practicable, as an average, under full demand.

The effect of a slackened demand is to increase the investment cost and operating cost per ton of coke. On the by-product oven plant, owing to the relatively high cost of these items, a slackened load means greater increase of costs. If, for example, the rate of operation should be cut in half, the cost of coke by the by-product method would be increased so much more than in the bee-hive process that the former would show either a loss or a very slight margin of profit.

Certain less tangible advantages in the by-product oven have influence in promoting its acceptance by the steel industry. Among these are (1) regularity and uniformity of products; (2) ready control of coke quality through the juxta-position of consuming and producing plant, and the adaptability of the by-product oven to control; (3) possibility of mixing coals in the by-product oven and of using coals not capable of being coked by the bee-hive method; (4) the convenience and economy of coke oven gas and of tar as fuels in the steel plant.

The gain for the by-product oven system from these items of more or less general improvement in conditions is no doubt greater in the aggregate than the actual profit from year to year in plant operation and from sales of by-products. To this may be ascribed the gradual turning that has occurred from the old wasteful coking method, to the modern recovery process, rather than to any great confidence in a lowering of actual coke making costs or a desire to conserve the coal resources.

The Processes of Gas Manufacture (by coal carbonization).

Description of these processes in detail is to be found in Chapter 12. A general discussion of the gas manufacturing industry and its problems, also, is presented in Chapter 4, following.

Here, in respect to the relative position of the coal gas retort among the various means for industrial coal carbonization, it remains to point out distinctive features and probable development.

The Horizontal Retorts. Reference has been made to the relatively small size of unit carbonizing charge in gas retorts as compared to that in coke ovens; also to the relatively greater speed with which small thin charges can be carbonized. There appears to be a trend in the industry, unmistakably, toward larger charges in the gas retorts and toward fuller charging, in order to reduce the intensity of the degradation of the coal-volatiles in the superheated free space of the retort.

The limit to which this development of unit size will go cannot be predicted with any approach to certainty. It will depend on many considerations such as (1) flexibility of the equipment in meeting variable demand, (2) the extent of variation in load to be caused by development of new uses for gas, (3) relative economies on the basis of respective investment costs, operating labor, and gas making capacities, (4) quality, yields and values of coke and by-products, (5) quality and yields of gas.

Whether a horizontal position of the carbonizing chamber, or an inclined position, as is used in some types, has any inherent advantages warranting its retention to compete with the vertically-arranged chambers which logically economize the labor of charging and discharging, remains a question on which there is difference of opinion. The horizontal retorts have their advocates and new installations are being made.[3]

The old type of horizontal, however, of a small charge (350-500 pounds) and with one end stopped, operating with relatively large and highly-heated free space above the coal, so as irretrievably to destroy by heat the oils and tars, the valuable hydrocarbons and the ammonia, and to produce carbon, heavy pitch, naphthalene, and other such objectionable degradation products, is happily becoming obsolete, as is the candle power requirement in gas which has been the only excuse for this system of coal carbonization.

[3] Alwyne Meade, "Modern Gas Works Practice," pp. 46 and 93.

The modern horizontals carbonize larger charges (1,500-1,800 pounds), are filled to within 3 or 4 inches of the top and may be discharged by a ram, pushed *through*. They are, in a sense, the vertical retorts laid down horizontally, except that they allow a channel of free space above the charge, a distinctive feature possibly lending some advantage.

Vertical Retorts. The vertical retorts allow automatic feed and discharge essentially by gravity. Through this distinctive feature they economize greatly the labor of operation—and have clearly an advantage, to that extent, over other methods of coal carbonization. The prediction has been made, that some form of vertical carbonizing chamber, even for coke production, is the most likely form to endure, owing to its inherent economy of labor and of space.

Description of the types of verticals used in America and of the method of their operation is given in another chapter (pages 344-64). The vertical retort has been developed in this country to a daily carbonizing capacity, per unit, of 2 to 6 tons; in Europe it has reached 7.5 tons. This, by comparison, stands between the capacity of 0.8 to 2.5 tons in the horizontals and 15 to 25 tons in the coke ovens of full size; (half-length coke ovens especially designed for smaller unit capacities for the gas industry, have daily capacities of 6 to 10 tons).

Vertical retorts may be either continuous or intermittent in operation. More of the former are in use, owing to their saving in labor costs. In them the coal and carbonizing mass moves continuously downward by gravity as the coke is discharged at the bottom by a slow-turning ejector.

Development in the Size of Carbonizing Chamber. The justification for the smaller carbonizing units has heretofore rested in their flexibility, and the need of the small community for a gas plant of small and quickly variable capacity. It is questionable whether this will continue, under the conditions likely to arise with the increase of centralization of gas making and the use of larger stations with wide distributing areas. The relatively large unit capacities, as secured by coke ovens, give great increase of economy in production, when the load factor on the operation is high, and allow also a considerable flexibility by the judicious combination of coke oven carbonization and gasification of the coke into water gas.

There has been, accordingly, a rapid increase in the application of coke oven gas to public service use, with distribution in city mains, until in 1920 such use surpassed that of all other coal gas combined (see further, pages 29 and 68-9).

The vertical retorts, by their gradual increase of unit capacity, are reaching out to attain an equal production cost with that of the coke ovens. They are aided in this by their economy of labor and of discharging machinery, due to their vertical design, and by their special facility for recovering the heat of the coke and for steaming the charge to increase gas and by-product yields. When the vertical gas retorts shall have so increased their capacities, possibly by elongation of their cross section, or in other ways, that they constitute then in effect the oft-predicted vertical coke oven, with equal or greater thermal economy, equal coke and by-products, and the logical increase of economy in labor and operation, above that of the horizontal coke oven, then will have been attained a rational and advantageous blending of the two systems.

Such a development, however, may in the course of evolution of gas manufacture, be outstripped, in thermal efficiency and costs, by some method of "complete gasification" of coal, many of which are under development, processes for carbonizing coal and gasifying its solid residue—by steam or air—in one operation. Such processes, however (see pages 368 ff., Chap. 12), are capable of yielding only a gas of medium or low heating value, as compared to that of the carbonizing retorts and ovens.

Coke and Gas Manufacture—in One and the Same Establishment. For many years a conviction remained firmly rooted in the coal carbonization industry, that good gas and good coke were not practically to be obtained in one and the same operation. It was held that the production of high-grade gas in suitable yields precluded the simultaneous production of good metallurgical coke. Conversely, the making of coke in ovens of such width and at such temperatures that the rate of carbonization was slow, appeared at one time to render impractical the recovery of good gas in commercial yields.

This idea has been almost completely dispelled by the advent of more rapid coking—with improved yields of gas,—the better construction of oven walls to lessen infiltration of air affecting gas quality, and the attainment of higher thermal efficiencies resulting in greater surplus gas yield. The coal gas from coke ovens has been found, not only to be of the same nature, in general, but of a grade as high, when carefully produced, as that from gas retorts. The use of high temperatures and rapid coking does not necessarily depreciate the quality of the coke, if the coal mixtures used are suitably chosen.

Coke ovens, as has been previously noted, are actually, in America, sending more gas through city mains than all other coal-gas producing equipment, and this, in many cases, with simultaneous production of good metallurgical coke.

Vertical gas retorts—primarily operated for gas—are in many cases producing good coke which has a ready market, partly for metallurgical purposes.

Coke, in recent years, has been more and more applied as a generator fuel in water gas manufacture—displacing anthracite coal. Such use leads to the combining, in one gas-making establishment of coke ovens or vertical retorts with water gas sets, to form a self-contained plant for producing mixed coal and water gas of high grade at relatively advantageous costs. By the contiguity of the two operations and the possibility not only of economy in labor and in transport of materials, but also of improved thermal efficiencies by the charging of hot coke to the generators, of small coke to gas producers for heating the ovens, and the use of waste heat boilers, a high percentage of over-all efficiency and relatively low costs of manufacture are attained.

If such a combination plant is to avoid the production of a surplus of coke—to be marketed—it is necessary to restrict the coal gas to a maximum of about one-quarter of the total gas output. The following data of average operation show this relationship:

TABLE 8.

Combined Coal Gas and Water Gas Plant, Self-contained.

Yield of coke in ovens or retorts		69.0 per cent.
Coke required in producers for heating retorts	12.0	
Coke breeze used in steam production	3.0	
		15.0
Net coke available for water gas generation		54.0 per cent.
Coke used per 1,000 cubic feet, in water gas generation		32 pounds
Water gas made from 1,080 pounds coke (54 per cent. on one ton of coal) 1,080/32 × 1,000		33,800 cubic feet
Coke oven or retort gas per ton, using moderate steaming at end of period		12,200 " "
Total mixed gas per ton of coal		46,000 " "
Percentage, coal gas	26.5 per cent.	
" water gas	73.5 per cent.	
	100.0 per cent.	

When an outside market is at hand for a part of the coke at favorable prices, it is frequently found profitable to increase the relative proportion of coal gas in the output and make a surplus of coke over and above the water gas requirements.

New Gas-Making Processes under Development.

Complete Gasification. Those processes which convert the combustible portion of coal completely into gas in one operation are known as "complete gasification" processes. Strictly it is not a new system since the common gas producer in which bituminous coal is completely gasified by blowing with a restricted quantity of air, aided by steam, falls plainly under the definition given, and the water gas generator using bituminous coal is another example now in use to some extent for city gas manufacture.

The common interpretation, however, of *complete gasification* embraces only those processes which make use of the heat of the blast gases to bring about low-temperature carbonization of the raw coal in one part of the apparatus and which make thus a gas of somewhat richer quality (in heating value) than either producer gas or blue water gas.

Several of these processes, which are under trial commercially, are described in another chapter. In most of them the essential feature is the enrichment of the hot water-gas—as it leaves the generator—by passage through a superimposed chamber holding the raw coal in a state of preliminary decomposition at relatively low temperatures. This upper carbonizing chamber is heated, not only by the sensible heat of the water gas passing through, but by the heat, also, of the blow gases in alternate periods passing *around* the carbonizer in checker-brick chambers or flues. In these latter flues some combustion takes place in order to utilize fully the latent and sensible heat of the blow gases. The coal after becoming partially carbonized in this way, descends into the generator where it is gasified. (See pages 368-75, Chapter 12, for detailed description).

Such a scheme is a rational attempt to avoid or lessen the thermal losses and the labor and equipment costs of unnecessary steps in the two-stage coal-and-water-gas process which has just been outlined. It is apparent that the losses of heat and the expenditure of labor and machinery in the discharging of coke from the ovens and its transfer to water gas generators are avoided in great measure by the combined or complete gasification process. There should be logically also a better recovery of heat from the gases, even if waste heat boilers be used in the two-stage process.

Complete data for comparison of efficiencies and costs by the two methods are not at hand.

The drawback to general acceptance of complete gasification in America, aside from its lack of adequate technical development, has been the low calorific quality of the gas produced. Regulation by law of the calorific value of publicly distributed gas, necessitates in most of the States at the present time a thermal value of over 500 B.t.u. per cubic foot, whereas the processes of complete gasification, thus far proposed, produce a gas of not over 375 B.t.u. Enrichment would be possible, but has not held out a strong appeal commercially in comparison with present methods.

It will be found advisable, and even economically necessary, in all probability, to maintain the heating value of publicly distributed gas above a certain minimum, high enough so that the increased costs of distribution, that is, of holders, pumping, piping, etc., for the leaner gas, will not counterbalance the gains in efficiency of manufacture. Gases of relatively low content of nitrogen, and carbonic oxides—as, for example, coke oven and retort gases—are relatively also of low specific gravity, and require therefore less power to effect their distribution through pipes. These factors are likely to act to retard the acceptance of complete gasification processes in full substitution for the straight carbonization methods.

With complete gasification, on the other hand, cheaper grades of coal may be used; in fact many of these coals, not of a highly caking character, are preferable for this purpose to the high grade gas and coking coals. Important gains in economy are thus likely to arise from the use of relatively low cost coals, saving much also in railroad haul. Their possible disadvantage in sulphur content may in part be overcome by new and improved processes of gas purification—such as the liquid purification process (pages 310-11, Chapter 11) recently developed and successfully applied on a large scale.

There is promise of large expansion in the use of gas for industrial and domestic heating, and of fuel economy and conservation of the coal resource thereby, when regulation of gas standards shall be modified so as to permit manufacture and distribution of a lower-standard gas produced by methods of improved efficiency and economy, with a rate structure suitably drawn to appeal to the large consumer. There is need of the encouragement, which such a modification of requirements would bring, for engineering research, to improve further the new processes of manufacture in this country.

The Use of Oxygen in Gas Making. Among the new developments which are likely to have important influence on the future trend of gas-making methods, is the use of oxygen in gasifying coal. This development is under way. It is not, however, directly concerned with coal carbonization, except as it may be used in connection with complete gasification processes, wherein low-temperature carbonization plays a part.

The subject is again referred to in Chapter 12, pages 375-7, where articles from the literature bearing thereon are listed.

It is apparent that in a complete gasification process, using alternately a blow period to maintain the heats and a "make" period to generate water gas by the action of steam, the blow gases are rendered relatively valueless when air is used—owing to the large volume of nitrogen introduced. If oxygen, possibly somewhat diluted with air, be used, the blow may be so managed as to produce a gas largely made up of carbon monoxide, or the "blow" and the "make" may be combined by introducing continuously a steam and oxygen mixture, producing "blue" water gas, enriched in small amount from carbonization of the coal in the upper sections of the generator.

The use of oxygen instead of air makes possible the inclusion of the blow gases with the make, and thus the decrease of thermal losses.

The vertical retort—used ordinarily for carbonization, may be blown, during carbonization, alternately with steam and oxygen—in limited amounts—thus more or less gasifying the coke, near the bottom, without introducing the diluent nitrogen of the air. Largely increased yield of gas is thus obtained and its quality controlled by the degree of steaming practiced. The thermal efficiency theoretically is raised by the use of oxygen.

These processes are in the experimental stage. One difficulty to be overcome lies in the control of temperatures, owing to the tendency of an oxygenated blast to raise the heat quickly at the point of its admission until the brick work of the linings may be burned out.

The cost of oxygen is now prohibitive, but when methods are developed on a basis of very large production and to the point of only a medium concentration of the oxygen-air mixture, not requiring compression into small containers—it appears likely that practical costs can be attained.

There appear to be possibilities therefore that future development of the application of oxygen in gasification of coal may so improve the thermal efficiency and quality of gas to be obtained in complete gasification processes that these latter will offer advantages not to be ignored in the up-building of the technique of the gas industry.

Low-Temperature Coal Carbonization. In this chapter is presented the broad aspect of so-called "low-temperature" carbonization of coal, in relation to the older and better established systems using high temperatures, in order to give, thus, as nearly as possible, a true economic perspective in the field. Technical detail of progress in low-temperature carbonization is to be found in Chapter 13.

Much attention has been given this subject in recent years and a confusion of processes brought forward and tried. The greatest success industrially has been attained in Germany and England, where, on the one hand, the prospect of securing by this means a much-needed re-inforcement of the oil supply has held out a tempting bait to the investigators, and, on the other, especially in England, the making of a good clean solid fuel for domestic use has been a prime object, and has led to important commercial development.

It cannot be said, however, that in any country, as yet, the system has attained a degree of commercial success which stamps it as economically sound. A longer period of test is necessary before that goal can be reached.

To make the system an economic success, the indispensable agency is a steady and permanent market for the products, at prices such as will pay the costs and yield a profit. It is not enough that the thermal efficiency of the process may be higher, that the total thermal value of oils and gas and semi-coke may be greater than that of tar and gas and coke in the high temperature systems, but there must be also a commercial value in these products commensurate with the relative cost of their manufacture. Up to this time, costs, owing to low capacity in production, have been relatively high, and the market for the somewhat unusual oil secured by this system of carbonization, as well as for the semi-coke, has not been established on a high enough level to cover these high costs. The whole matter, therefore, must be considered as in a stage of development, and, in a large sense, on trial.

"Low-temperature" carbonization, whatever may be the exact temperature limits defining it, is properly to be characterized by the fact of its reducing to a practical minimum the secondary decomposition of the products volatilized in carbonization. Coal carbonization being itself a thermal decomposition process, and the primary products thereof being, in any case, highly susceptible to further disintegration by heat, there can be no hard and fast line drawn as to what reactions are primary and what secondary. In most common acceptance of the term, low-temperature carbonization is applied to those processes wherein the wall temperatures of the retort or oven do not exceed 700° Centigrade (or about 1300° F.). This temperature marks roughly the rapid hastening of those secondary decomposition reactions which break down the volatilized coal products largely into gas and heavy carbon nuclei.

The object of low-temperature carbonization is to avoid such degradation of the early-formed products, and recover them in the form of oils carrying greater potential value, both in heat units and for chemical uses. The solid residue or coke thus obtained is desired also as a smokeless and generally useful fuel, more easily ignited than the usual hard coke of the high temperature processes.

Analysis of the Gain by Low-Temperature Carbonization. Estimating the yields of low-temperature carbonization liberally, the following appear to be essentially the gains and losses as compared to high-temperature coke oven carbonization:

TABLE 9.

	Per Net Ton of Coal			
		Gained		Lost
Oils	16 gallons at $0.06,	$0.96		
Coke	80 pounds at $0.005,	.40		
Ammonium sulphate			18 pounds at $0.025,	$0.45
Gas			4.2 million B.t.u. at $0.30,	1.26
Heat used to carbonize	0.8 million B.t.u. at $0.30,	.24		
Total	Gains,	$1.60	Losses,	$1.71

The principal advantage ordinarily claimed for low-temperature carbonization is its high yield of oils. When, however, the disposal of these is assumed to be for fuel, at a fuel-oil value, the gain from this item is hardly sufficient to balance the loss in gas. The gain in coke is balanced by the loss in ammonia.

Accordingly, on the basis of yields and their commercial values, we find little if any advantage in low-temperature carbonization, *unless* the oils (and semi-coke) may have peculiarly enhanced value due to special applicability in certain fields. It is here that the main hope and promise of the system appears, in the special applicability of its products to meet certain demands, for an acceptable smokeless domestic fuel, for wood-preserving oils, for possible lubricants or chemical derivatives. This is a matter, however, of future development.

The other element of hope for economic success in the use of the system lies in its being able to simplify the carbonizing plant and reduce costs—as compared to those of the elaborate equipment and operation in high-temperature carbonizing. This, it has not yet done, owing to the difficulty of securing a reasonably rapid heat penetration through the coal so as to have commercially practical operating capacities, and the necessity in most instances of adding to the operation the expensive process of briquetting of the solid residue. These difficulties, so far, have maintained the costs at a level above that of the gains in product-values.

The big field for low-temperature carbonization is likely to be found—not in competing with the established systems of coke and gas making, but in supplementing them in the territory and for the coals suited better to its peculiar methods. The Interior and Western territory, for example, needs a smokeless fuel, and in that territory the local coals, not well-suited to high temperature coking, can make such a fuel by low-temperature carbonization, with advantageous recovery of oils in important amounts. When a process shall have been developed, securing relatively low costs by simplicity of plant and operation, and a rate of output per unit of investment comparable with that of high-temperature coking, it is to be expected that expansion in the application of this system of coal carbonization in the direction indicated will follow quickly.

The very rich gas obtained by low-temperature coal carbonization is an asset too often overlooked. Its quantity is small but its quality—owing to a rich content of saturated and unsaturated paraffin hydrocarbons—is very unusual. To enrich leaner gases for public distribution, when such disposal can be made to an adjacent gas plant not requiring long transmittal of the rich hydrocarbon gas, appears to be a favorable and profitable outlet for this product. It is a waste of a high-grade, special product of this kind, to burn it under the retorts as carbonizing fuel.

Chapter 4.

The Gas Industry.

General. The gas industry, in the future, is destined, in all probability to become the largest exponent of coal carbonization. This position it does not yet hold, but, the rationality of gaseous fuel for heating purposes, industrial and domestic (see pages 76-7) lends strength to the chances that this fuel, when its cost becomes less, may outstrip coke in the field of general fuel application.

The processes of gas manufacture, using coal carbonization, are described in another chapter (pages 339ff., Chapter 12). The relations between the various coal carbonization systems, on a broad economic basis, are discussed in Chapter 3, just preceding. It remains, in the present chapter, to outline briefly the problems of the gas industry, and its prospects, setting forth the importance of the industry, now and in the future, as a part of the general scheme of fuel utilization, and as a means toward the end of a rational and economical use of coal through carbonization.

Coal Carbonization in the Gas Industry. In 1920, about one-third of the gas publicly distributed through city mains, was obtained by coal carbonization.[1] In addition to this, in 1920, 177 billion cubic feet of coke oven gas, an amount equal to more than half of the publicly distributed gas of all kinds, was sold direct to mills without passing through the medium of public utilities.

The records thus show that, of all the manufactured gas produced and sold in the United States, in 1920, coal carbonization furnished 55.5 per cent. The balance was water gas and oil gas. A large amount of coke oven gas, not included in the above, was manufactured and used in heating the ovens or was "bled" to the air.

Figure 11 illustrates the rate of growth of the sales of total manufactured gas, from 1898 to 1920, and relatively also that of coal carbonization gas.[2]

The growth in percentage of coal gas became appreciable only when the coke ovens, about 1910, began to increase materially their sales of surplus gas. The coal gas from bench retorts, in fact, in its relation to the production of water gas, decreased markedly from about 1907.

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[1] Manufactured Gas and By-Products in 1920, *U. S. Geological Survey,* Mineral Resources of the United States, 1920, II, Chapter 35, pp. 446-7.

[2] Adapted from data of *U. S. Geological Survey,* Mineral Resources of the United States, 1920, II, p. 445.

The relative magnitude, in the future, of coal carbonization as a factor in the gas industry is a question not easily answered. Favoring the increase of its importance are (1) the fact of the rising price and probably approaching shortage of oil used in making water gas,[3] and (2) the comparatively low thermal efficiency of the water-gas process and of the cracking of oils in its enrichment. Others factors, however, exert a counter influence, favoring the retention of water gas manufacture to fill out a quota in the total gas production, until it can be displaced economically by new and improved processes, possibly by some form of complete gasification or of gasifying with oxygen, which are capable of using the coke resulting from straight carbonization.

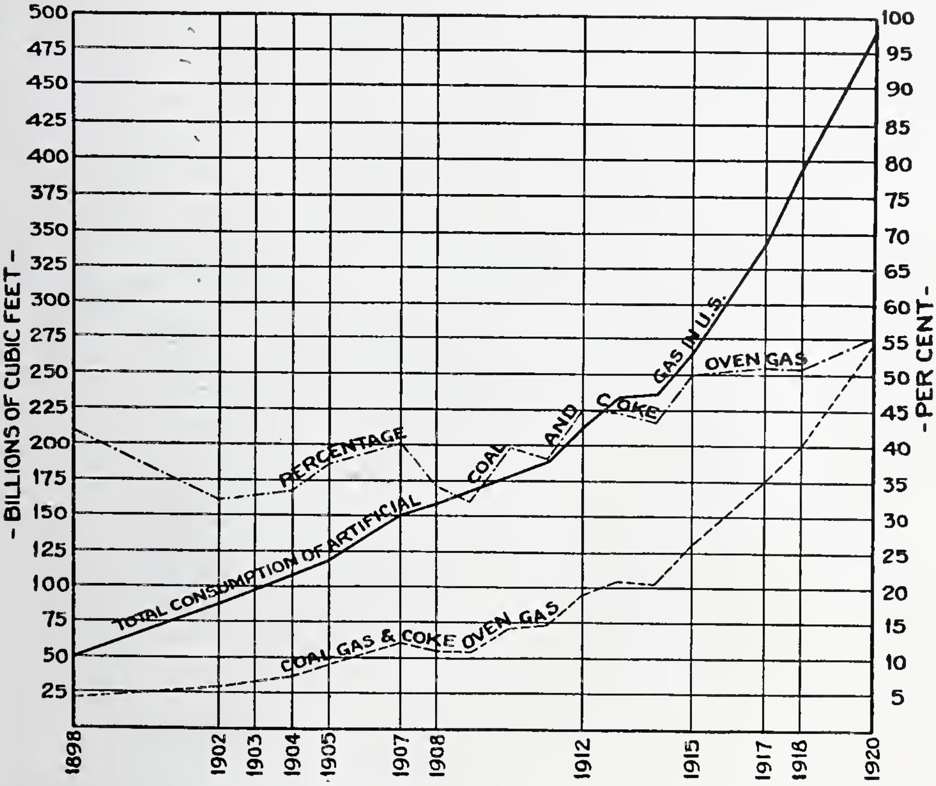

FIG. 11.—Growth of Gas Sales in the United States, showing especially the relationship of coal carbonization gas to the total of manufactured gas (adapted from data of the U. S. Geological Survey).

These factors favoring water gas are (1) its ability to utilize coke as a generator fuel, and to relieve thus, in a measure, the coke ovens or retorts of the necessity of finding other markets for their coke; (2) the relatively low capital costs and operating costs of water gas per unit of output, putting on the enterprise a lesser burden of increase of fixed charges from a variable and seasonal load; (3) the trend of gas standards toward a lower B.t.u. requirement, calling for a materially reduced expenditure of oil. When the annual load factor on the plant, due to seasonal variation in demand, is at a low figure, the less costly water gas installation serves well to carry the intermittent load, and thus during slackened production to build up less of a capital charge on the unit of gas output than would accrue from a similar condition with coke ovens or retorts.

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[3] See Report to American Gas Association, of Committee on Gas-Oil, 1920, W. H. Fulweiler, Chairman, pp. 390-407, Techn. Sect. Sessions.

The future relative production of coal gas and water gas will be controlled most largely by the scarcity and price of oil. There is a point where this price raises costs sufficiently to counterbalance the gains derived from lower investment in plant.

It has been shown (page 62) that a combination water gas and coke oven plant operates without a coke surplus, when the water gas is made to constitute three-quarters of the output and the coke oven gas one-quarter. There is no reason to conclude, however, that such will be the average proportion of coal gas in the ultimate send-out of the gas industry. In fact, this proportion is likely to be much higher. It will be higher, roughly, in the degree that coke is sold for other purposes. As coke is disposed of to the metallurgical industry and for domestic use, its corresponding quota of coal gas becomes available, and no production of water gas in connection therewith is necessary as a means of coke disposal. Water gas made from lump anthracite as a generator fuel is likely to be a factor of vanishing importance as the cost of this fuel becomes prohibitive.

The present figure of 55 per cent. for the proportion of coal gas in the manufactured gas industry is likely to be maintained or exceeded.

Rate Structure—The Cost of Gas and the Charge to the Consumer. The largest factor, unquestionably, in the future expansion of the manufactured gas industry, is the question of an equitable system of charges to the consumer. Under a flat rate the large consumer, say the industrial user, whose demand, on account of its steadiness, is most desirable, pays an inequitable proportion of the fixed and overhead costs of gas production and distribution. The charge to him, therefore, under a flat rate, cannot be made low enough to secure much of his steadying and profitable trade.

As long as the manufactured gas industry is concerned chiefly with domestic trade (including restaurants, hotels, laundries, and the like), its load will be extremely variable, and its overhead expense, the cost of being "ready to serve" at the peak load, will be high in relation to other manufacturing industries. A three-part rate, consisting of (a) the "customer charge" (a fixed amount per annum), (b) the "maximum demand" charge (a per-annum charge based on the maximum amount used in any hour or 24-hours), and (c) the "commodity" charge based proportionately on the amount actually used, is a nearer approach to an equitable system of charges in the gas industry than can be obtained by the flat rate.

A large and permanent expansion into the industrial and house-heating fields is likely to come only through an agreement between the utilities and the regulatory bodies upon some such adjustment of charges.

The Report of the 1923 Committee of the American Gas Association on Rate Structure, emphasizes these points as follows: "The future of the industry presents a problem for the most serious consideration. There is no general per customer increase in the cooking load. The situation would be serious indeed if it were not for the fact that uses for gas loom up that stagger the imagination. But this prospective business is quite out of reach with poorly designed rates that do not reflect true costs. Your committee, therefore, recommends that members give this matter earnest consideration and take such measures as may be practical to bring to the attention of public utility commissions the advantage to customers and companies alike of providing rates that would enable us to compete for large consumption business. The great increase in the volume of gas required to be produced and the improvement in plant load factor following the connecting up of such business would inevitably result in lower costs in which even the small customer who is now carried at a loss would eventually share.

"Gas for house-heating is one of the big opportunities. A rate structure is urgently needed that will make house-heating by gas possible and hasten its development. But it must be done at a profit. The rates must, therefore, be based on accurately determined costs of this specific service. Since new production capacity will have to be provided on the basis of the *daily* demand of house-heating, the *annual* load factor of this business must be given careful consideration. The effect of house-heating on distribution capacity is, of course, a function of *hourly* demand."

In this Report, (Proceedings A. G. A., 1923, page 139), is given the allocation of actual costs by one gas company, on a four-part plan. (Table 10.) This plan is similar to that outlined above on a three-part basis, except that the "maximum demand" charge is split into two items, one for manufacturing (the maximum 24-hour demand) and one for distribution (the maximum hourly demand).

From an analysis of these data it appears that this plant sold gas throughout the year at an *average* daily rate of 15,104,000 cubic feet, but that its maximum day's demand was 20,000,000 cubic feet. Its maximum hour was 2,400,000 or at the rate of 57,600,000 per day. It was required to be "ready to serve" in one hour 2,400,000 cubic feet, but it was not required to manufacture at that rate, since storage capacity presumably could take care of a part of the hourly peaks. The annual load factor, referred to the 24-hour demand, was 75.5 per cent. and the annual load factor referred to the hourly demand was 26.2 per cent. The latter represents the distribution load factor, and the former (or a figure somewhat less) the manufacturing load.

TABLE 10.

SUMMARY OF FOUR PART COSTS.

(From American Gas Association Committee on Rate Structure Report, 1923.)

	Total	Per M Cu. Ft.	Customer Cost	Per M Cu. Ft.	Manufacturing Demand	Per M Cu. Ft.	Distribution Demand	Per M Cu. Ft.	Commodity	Per M Cu. Ft.
Production	$2,561,407.86	.4646			$100,000.00	.0181	$ 10,000.00	.0018	$2,451,407.86	.4447
Distribution	442,730.89	.0803	$ 261,500.00	.0474			161,730.89	.0293	19,500.00	.0035
Municipal lighting	373.74								373.74	—
Commercial	194,167.64	.0352	194,167.64	.0352						
New business	48,955.94	.0088	24,955.94	.0045	6,000.00	.0011	6,000.00	.0010	12,000.00	.0022
General	147,042.23	.0266	73,462.23	.0133	18,395.00	.0033	18,395.00	.0033	36,790.00	.0067
Retirement expense ...	225,000.00	.0408	81,000.00	.0146	83,000.00	.0150	61,000.00	.0111		
Taxes	651,605.00	.1182	150,000.00	.0272	154,000.00	.0279	111,176.60	.0202	236,428.40	.0429
Return on investment..	1,350,000.00	.2448	485,000.00	.0881	500,000.00	.0907	365,000.00	.0662		
	$5,621,283.30	1.0193	$1,270,085.81	.2303	$861,395.00	.1561	$733,302.49	.1329	$2,756,500.00	.5000
Capacities			112,070		20,000,000		2,400,000		5,513,000 M	
			Average No. of Customers		Cubic Feet per 24 hrs.		Cubic Feet per hour		Cubic Feet Sales year 1922	
Unit Costs			$11.34 per annum per customer		$4.30 per annum per 100 cu. ft. of 24 hr. demand		$30.54 per annum per 100 cu. ft. of hourly demand		$ .50 per M cubic feet	
			$ .95 per month		$ .36 per month		$2.50 per month			
					66.44 per 100 feet of hourly demand					

If it be assumed that these data represent an average character of business, it is apparent that the distribution load factor in the gas industry is low, or in other words the hour-to-hour variation in load is great. The growth of industrial gas sales should increase this load factor. House-heating sales also would improve this load factor but on the other hand, owing to their seasonal variation, would lower the manufacturing load factor.

The table is instructive in illustrating (see second column) the distribution of the total cost per thousand ($1.02) among the items of production ($.465), capital or investment expense ($.404), distribution ($.080) and "general and commercial" ($.071). (It is to be borne in mind that an important part of the investment expense is chargeable to distribution.)

This company's allocation of these expense items to "customer" cost, "demand" costs, and "commodity" cost, are shown in the several columns.

Whether such a rate structure deals fairly with the future very large consumer of industrial gas, or whether he should be allowed also the benefit of a "step-rate," diminishing with increasing use, is a large problem, to be solved through experience.

The Question of Gas Standards. Close to the question of a suitable rate structure stands the matter of required standards of gas quality, as a factor affecting continued expansion of the industry. Within certain limits gas of lower heating value per cubic foot is less costly in manufacture—per unit quantity of heat in the gas—than is gas of the higher heating value. It is also—within somewhat narrower limits—not materially more costly to distribute than the higher heating value gas, and its curve of cubic-foot consumption, for equal performance, does not rise in proportion to the decrease of heating value.

These facts—meaning essentially lowered costs, opportunity for lowered sales prices, and increased expansion and diversification in the industry—have led to a vast amount of discussion of the subject of suitable standards, and to a comprehensive study thereof by the gas industry and by public service regulatory commissions.

The files of the Proceedings of the American Gas Institute, the American Gas Association Monthly, the Reports of Gas Standards Committees, and the abstracts of rate-case decisions (issued by the American Gas Association) are replete with information on the progress being made in America in solving the problem. The subject is so large that it cannot be treated here.

The Report of the 1923 Committee on Gas Standards and Service, American Gas Association,[4] may be quoted in part, to show the attitude of the organization toward further and more thorough study of this subject:

"The enforced education of the gas industry itself, respecting gas standards, would appear to be one of the most pressing, as well as important, activities of the Committee. This applies especially in those localities where the need of additional supplies of gas for house-heating and industrial purposes may become acute, and where the maintenance of good service becomes a serious problem.

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[4] By J. B. Klumpp, Chairman, in *American Gas Association Monthly,* Oct. 1923, Vol. 5, p. 637.

"It would appear to be a wise policy to first inform ourselves of all matters pertaining to gas standards and to be able to support such knowledge with facts. If we are thus equipped, and the need arises, much can be accomplished with regulatory bodies to discourage in a large measure, the inclusion of inadvisable specifications in proposed rules."

In the interests of economy of fuel, increased thermal efficiency of the translation of the latent energy of coal, into utilized energy through the medium of gas, it is desirable that such a standard be permitted, or such a latitude in choice of standard, that a manufacturing process of high thermal efficiency and low costs can be employed.

The trend in the period following the World War has been toward a lower heating value standard and toward abandonment of the illuminating standard. The State of Colorado, by order of its Public Service Commission to become effective Oct. 1, 1923, granted to the gas companies freedom of choice as to heating value standard of their product with the provision of certain guarantees of uniform and satisfactory service. A part of the published opinion of the Engineer of the Commission (H. B. Dwight) as to the advantages of this system[5] is quoted here to illustrate the increasing favor accorded to such methods of control in this country: "It appears that marked improvements in gas production methods and apparatus are being made, and that a lowering of B.t.u. standards is an essential part of the present trend of these improvements and is not necessarily detrimental to the consumer's service.

"The importance of a particular standard, so long as there is a fixed standard for the particular utility, in the judgment of the Commission's engineer, is of minor importance to other factors of gas production and sale. Much more important is uniformity of quality as to heating value, purity and chemical content, uniformity of gas pressure at point of use, proper adjustment of consumer's appliances to the standard in use, and a thorough, systematic inspection of such appliances.

"It is known that to produce gas which will conform to the Commission's present standard, each B. t. u. put into a cubic foot of gas over and above about 300 B. t. u. must be accomplished at a much higher cost per B. t. u."

In Great Britain, the Gas Regulation Act of 1920 (as also in some measure the Act of 1914), granted freedom of choice of standard of heating quality, with regulation as to maintenance of service, and adopted the "therm," or 100,000 B.t.u.'s, as the basic unit for charges. There has been sufficient opportunity, therefore, to observe the working of such a system.

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[5] American Gas Association, Information Service Letter, No. 45, Sept. 1923.

Coal gas, in England, forms a much larger percentage of the total gas output than in America. The new system of regulation has resulted, therefore, in the practical development of lower B.t.u., lower cost, coal gas. The steaming of vertical retorts (to secure more gas, at lower B.t.u.) has been used with marked success, and complete gasification processes have, in some measure, come into successful operation.

In June 1921 the average of all declared standards under the British Act was 467 B.t.u. Of the companies selecting new standards, 94 per cent. selected values between 450 and 500 B.t.u.[6] This is to be compared with American practice of furnishing, by requirement, 520 to 630 B.t.u. There is said to be a trend now (1923) among British companies [7] toward choice of a somewhat higher standard than in 1921, chiefly due to the factor of costs of distribution.

It is to be emphasized that, in the matter of standards, the greatest amount of progress, bringing expansion of the industry, is likely to result from a system giving freedom of choice of B.t.u. quality, under regulation as to service and charges. Such a system permits adjustment of manufacturing methods to local conditions and to the use of economically obtainable coal.

Some Possibilities on the Basis of Lowered B.t.u. Standards. By moderate concessions in present required American B.t.u. standards, the following technical advantages in manufacture would be gained:

1. From by-product coke ovens, the total run-of-oven gas, of 540-570 B.t.u. and 11,000 cubic feet per ton, becomes available, without enrichment, and, if steaming of the ovens is used, 12,500-13,000 cubic feet per ton, of 520-540 B.t.u., these yields being 7 to 20 per cent. greater on a B.t.u. basis than those possible under a high B.t.u. standard. The loss in coke, by gasification, in the case of steaming, is less than corresponds to the increase of gas. Coals less costly than the high-grade gas and coking coal then become available.[8]
2. In a combination coke oven and water gas plant, on lowered B.t.u. standards—less oil is required for enrichment. In fact, on a standard of 450 B.t.u., the use of oil could be dispensed with, and a 50-50 mixture of coke oven gas and blue water gas made, passing part of

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[6] American Gas Association, Information Service, Sept. 1921.

[7] According to a statement of Dr. E. W. Smith, Technical Director, Woodall Duckham & Jones, Ltd., London, England, in an address to the American Gas Association, General Session, Oct. 18, 1923.

[8] A prevalent impression, however, that coke oven gas as now made and under present gas standards, is unsuited to city distribution, on account of its low heating value, requires correction, since coke oven gas, by use of good coals and care in manufacture, can be made of a quality to meet practically all requirements.

the latter through the charge in the coke oven for enrichment. This method reduces the thermal degradation of the coke oven gas, and improves the yields. In such a plant there would be a surplus of coke for outside sales.

3. In vertical retort practice a lowered B.t.u. standard permits steaming of the hot coke in the bottoms of the retorts, thereby utilizing part of the sensible heat of the coke to make additional gas. That yields are thus increased and costs lowered per "therm" has been demonstrated in British experiments. (See page 367, Chapter 12.)

4. By a lowering of B.t.u. standard requirements development is encouraged in the field of complete gasification (pages 62-3 and 368-75) and in low-temperature carbonization to provide enrichment for the gas from such processes, such a combination promising improved yields and lowered costs.

Rationality of Gas as a Fuel. When coal or coke or wood is burned, it is, to a large degree, gasified in the process. The burning gas, or the flame, acts as a medium for the transfer of heat energy.

The principle should be self-evident that by concentrating this process of gasification of solid fuels into one central plant, where the scale of operation is large, and all known refinements and economies can be advantageously applied, a material reduction of losses and inefficiencies becomes possible. Counter to this advantage stands chiefly the question of economical transmission of the gas-form energy from the central plant to the user. The losses thereby incurred have proven to be inconsequential; the costs, while high, are not prohibitive, progress in reductions continually being made, and, by comparison, the distribution costs of solid fuels being by no means small.

In application, gas permits many decided gains. The absence of ash and clinker, and the complete escape from the burden of waste in unburned fuel, are chief among these gains. S. S. Wyer, in an article issuing from the Smithsonian Institute,[9] states that actual analysis of the refuse from domestic coal-burning furnaces has shown an average content of 50 per cent. unburned coal.

A very important gain also by use of gas, both in industrial and domestic furnaces, results from the ready control of use as affected by demand. The facility of varying the consumption, and controlling, when desired, automatically, is much greater than with solid fuel.

There may be listed, as among the more important elements in the rationality of gas for fuel, the following:

1. Automatic control, the facility of regulation to suit requirements.
2. Delivery in furnace in ready-to-use form.
3. Vanishing cost of labor for firing and removal of ash.
4. Practicability of economizers to recover waste-gas heat; almost no requirement of a heated chimney for the sake of draft; reduced cost of chimney flue construction.

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[9] "A Study of the Mineral Resources of the United States as Applied to Pennsylvania's Resources."

5. No loss of unburned fuel.
6. In industrial application, the possibility of air preheating—by regeneration—to recover waste-gas heat.
7. Central production, resulting in a saving of railroad haul of coal, as related to present practice in coal distribution.

Industrial Application of Gas. Charles A. Monroe, Vice-President of the Peoples Gas Light and Coke Co. of Chicago, and a former President of the American Gas Association, in an address to this Association, October, 1923, on "The Importance to the Gas Companies of the Sale of Industrial Gas," [10] emphasized strongly the predominating part that industrial application of gas will play in gas operations and sales of the immediate future. His predictions were supported by concrete instances of rapid growth in this field, accomplished by systematic effort to secure and satisfy such consumers, and without the aid of a material reduction of price.[11]

The improvement of load conditions on the gas producing plant, secured through sale of industrial gas, has been dwelt upon in another connection, (page 73). Economies secured by the consumer may be mentioned here.

Gas is applicable in the industries chiefly for heating purposes, and not advantageously in the field of power production through steam. The greater over-all thermal economy of direct coal firing, in the latter field, except under occasional local conditions where a by-product gas would be wasted unless burned for such purpose, is explained in a previous chapter.

But for the reheating and reworking of metals, in the making of steel in open hearths, in crucible and pot heating, annealing, glass and pottery manufacture, baking, large-scale storage water heating, the economies secured by gas have been amply demonstrated. Even in comparison with oil, when shrinkage of the latter is considered, its requirement of storage and pumping, and the necessity of firing a liquid fuel with compressed air or steam, the relative costs and efficiency of gas are in most instances favorable to the latter.

Economy by the use of gas in industrial heating processes results in an important degree, from gains, incidental to the furnace efficiency —but not directly dependent thereon. These include (1) increased capacity of output, (2) labor saving, (3) uniformity of heat application and improvement of product, (4) control of length and character of flame by suitable air-mixing methods, (5) purity of fuel and furnace atmosphere, in respect to sulphur, soot and powdered coal ash.

Many records of such economies in practice are available. Professor H. M. Thornton, before the British Royal Society of Arts [12] has presented records of actual operation, showing in different sizes of heat-treating furnaces, fired by gas, a saving in fuel per unit of output, of 40 to 60 per cent. as compared to coal firing. For American conditions, W. Trinks,[13] in a series of papers on industrial heating-furnaces, shows the economies attainable by use of gas.

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[10] General Sessions Proceedings, American Gas Association, 1923.

[11] See also, on this subject, H. O. Loebell (Vice-President of H. L. Doherty & Co., New York), in *Gas Age Record*, 53, 41 (1924).

[12] *Journal of the Roy. Soc. Arts*, 68, 346 (1920).

Gas in the Home. Not only as a luxury fuel, desired for its convenience and cleanliness, but eventually also for efficiency and actual economy, gas will in time to a large extent displace solid fuel in the home. Although its early use was mainly for lighting, this use forms now hardly 20 per cent. of the total demand for manufactured gas. F. C. Freeman, Vice-President of the Providence Gas Co., in a lecture on "The Gas Utility," 1921 [14] stated that the estimated present-day use of gas is 22 per cent. for illumination, 50 per cent. for other home uses and 23 per cent. for industrial use. "There are 6,400,000 domestic cooking appliances in use, 1,300,000 water heaters, 900,000 space heaters. There are 7,600 hotels, 2,300 clubs, 74,000 restaurants, and 2,000 other institutions using gas for cooking."

The automatic gas water heater, either as supplied with storage tank, insulated for retaining the heat, or of the coil type heated only when used, is showing such economies, as well as convenience, that coal-fired water heaters are rapidly being displaced.

Central house-heating by gas, while courted but indifferently by the gas industry in general, owing to its uneven manufacturing demand, is being asked for, increasingly, by the consumer. In a number of American communities this load has already (1923) become an important one to the gas companies. The consumer finds it a convenience and a saving of time, labor and space. When these things are capitalized, together with the elements of cleanliness, comfort, and health, the cost, as compared to that of coal, is within reason.

The cost differential will decrease, furthermore, as suitable rate-structure on the 3-part basis with added step-rate for large consumers (see pages 70-72) is adopted, and as diminished requirements in B.t.u. standards permit lower costs of manufacture.

In 1923 the Denver Gas and Electric Light Co. reported [15] to the American Gas Association their records of actual data on a number of cases of residence heating and comparisons with coal. There was a 3-part rate of charge for gas, as follows:

(1) Customer charge	$9.00 per annum
(2) Demand charge, per 100 cubic feet of maximum hourly demand	$21.00 per annum
(3) Consumption charge, per 1,000 cubic feet of gas metered	$ .40 per M.

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[13] *Blast Furnace and Steel Plant,* 8, 327 (1920); also, same author, "Industrial Furnaces," Wiley & Sons, New York, 1923.

[14] *Amer. Gas Assoc. Monthly,* 4, 204 (April, 1922).

[15] Technical Section Proceedings, American Gas Association, 1923, Report on an Experiment in Residence Gas Heating at Denver, Colo., by T. M. Foulk and T. G. Storey.

The coal used, with which comparison was made, varied in character and cost, the average cost being between $10 and $12 per net ton. The gas was of 375-400 B.t.u. per cubic foot. The conclusion as to relative costs was as follows: "the cost of coal replacing one million B.t.u. of gas averaged 95 cents for hot air furnaces, 84 cents for conversions and 81 cents for gas boilers, or a general average of 89 cents for coal against $1.56 for gas." "In calculating the heating costs with coal, no charges for removal of ashes or janitor service have been considered. In some cases, where a fireman was employed the actual cash cost of heating the home, per season, with gas has been very close to the costs with coal."

As to relative thermal efficiencies these results showed an average ratio of B.t.u. fired, in gas as compared to coal, of 0.549 on equipment designed for gas, and 0.608 on converted coal firing equipment.

In other words the results showed an average consumption of gas as compared to 1 ton of coal (assuming gas of 400 B.t.u. per cubic foot and coal of 12,500 B.t.u. per pound) of 34.3 M. cubic feet in the one case and 38.0 M. cubic feet in the other.

The Load Problem, in Providing for House-heating by Gas. Owing to the fact that house heating offers its demand on the gas plant during only seven months of the year, and its demand, during the peak period, may easily exceed that of all other domestic demands combined, the problem of meeting economically this large seasonal load is a serious one. If added plant capacity, sufficient to meet this maximum demand, is used during less than 50 per cent. of the full year's time, its capital charge on the unit of output becomes more than double.

The suggestion naturally arises that the low periods in the load curve may be filled in with other seasonal loads. Refrigeration by gas is a possible development towards meeting the need, and the use of auxiliary storage water heaters fired by the house heating appliance in winter but separately fired in summer.

There is also the possibility that through the coöperation of regulatory bodies arrangement may be made to take care of the peaks of production in winter months by a gas of somewhat lower B.t.u. value produced by admixture of blue water-gas, producer gas, or the gas of complete gasification processes, whose capital charges are relatively low. Such relief, however, would be only partial, since it would not affect the inequalities of the distribution load.

The distribution problem, in fact, is probably at this time the most difficult one confronting the gas industry, as the manifold new uses for gas begin to multiply its sales. Much careful study is being devoted to this phase of the industry's development, and improvements and economies are being worked out. Among these, especially important are the developments in high pressure distribution.[16]

[16] *Gas Age Record,* 1922, 287 and 789; 1920, 469.

The Future of the Manufactured Gas Industry, as Affecting Coal Carbonization. Summarizing the matters presented in this chapter, the conclusion appears inescapable that gas is to become a fuel of very general application, and the growth in its use will, more than any other agency, lead coal carbonization to a place of predominating importance in fuel utilization.

The rationality of gas as fuel, and particularly of the distribution to the ultimate consumer of a mobile, efficient, clean and high-test fuel material, instead of the low-test, inefficient, dirt-producing and labor-wasting solids, will exert perhaps the largest influence in promoting this growth.

The costs of conversion of coal to gas and of distribution of the product to consumers, operate to retard progress, but constant improvement in cost relations is going on, and this factor will not long be a serious drawback. Even now domestic and industrial consumers, for many purposes, find that gaseous fuel, all things considered, repays its added heat-unit cost.

A suitable rate structure and a reasonable adjustment of the requirement of quality-standards will go far in promoting progress.

Manufactured gas, by processes developed comparatively recently, can be made cheaply from coal. The use of coke ovens or of vertical retorts, with steaming, has been established as a means of relatively low cost gas manufacture. It is fallacious to use, against these processes, the argument that coke disposal is a serious burden, and a financial disadvantage. Coke forms an excellent water-gas generator fuel and when properly sized can readily be sold also for general fuel purposes. A combined water gas and coke-oven or retort-gas plant can be self-contained, or can sell coke, as desired.

Complete gasification processes, especially those promising the use of cheap oxygen in their operation, to increase efficiencies, are under development, and will be a factor in the securing of low-cost gas.

Distribution—both as to costs and capacities—presents probably the most serious problem.

Chapter 5.

The Nature of Coal Carbonization.

General. Owing to the well-nigh universal rôle, played by carbonization, in the application of coal, if only as a step in the use process, whatever it may be, a vast amount of study has been devoted to the increase of knowledge of what coal is, chemically, and a scientific analysis of the mechanism of its carbonization.

While it may be conceded that some inconsistencies arise, as between the laboratory phenomena of coal decomposition by heat, and the analogous phenomena occurring in commercial coal carbonization, yet it is only through scientific study of these phenomena and a broad practical coördination of the knowledge gained in the laboratory with the industrial operation of carbonization processes, that real progress will be made in solving the technical problems of the industry and improving its status.

It can readily be seen that the task of adapting heat treatment, size and shape of retort, physical condition of the coal, steaming of the charge, and sundry other conditions and expedients, to the ends desired and to the kinds of coal available, is facilitated greatly by a knowledge of the fundamental reactions occurring or likely to occur.

Therefore in this chapter is presented chiefly an outline of what is known of the mechanism of coal carbonization and the theories most plausible in explaining the transformations that occur.

As to the constitution of coal the state of present knowledge is presented here only in very brief synopsis, and the reader is directed to other sources of detailed information on this phase of the subject.

In Chapter 11 (pp. 320-335), where the by-products of coal carbonization are described and their derivation traced, some of the reactions leading to formation of the constituents of coal gas, tar, and light oils, are explained. In order to minimize repetition these derivations are only briefly alluded to here.

Importance of the Mass Relations among the Primary and Intermediate Products in Carbonization. The reactions of carbonization are exceedingly complex. A wide variety of substances occur, solid, liquid and gaseous, changing constantly in character and concentration as the process goes on under changing conditions of temperature, rate of gas flow and amount of contact with solid surfaces.

There are hydrocarbons, of cyclic and straight-chain types, and combinations of the two, water vapor, carbonic oxides, phenolic bodies (hydroxyl derivatives of ring-formed compounds, either aromatic or hydro-aromatic), hydrogen, hydrogen-sulphide, ammonia and the nitrogen bases, not to include a large number of other substances in the lesser amounts, occurring in the mixture of volatilized products passing through and out of the carbonizing mass.

The exact application of physico-chemical laws of equilibria relationships and mass action to reactions occurring in such a heterogeneous mixture and under conditions so constantly changing, is exceedingly difficult. General tendencies can be determined by experiments in which the conditions of temperature and of atmosphere especially are carefully chosen to accord with certain phases of those of practice. But they find application only as cogs in the complicated machine of inter-dependent and often counter-acting influences.

It is infrequently, and perhaps inadequately, emphasized in studies of these reactions and in the theories resulting therefrom, that in early stages of carbonization the mass relationships among the products are very different from those of the final products. Oxygenated bodies, for example, are formed easily and early in coal carbonization.[1] In the products issuing from the plastic layer of partially fused coal, wherein a temperature of 375°-450° C. (707°-842° F.) exists, it is likely, in the case of an average coking coal, that water vapor constitutes at least one third of the weight, and that all of the oxygenated bodies present (water, oxides of carbon, and hydroxyl compounds in the tar vapors) make up, as an aggregate, half or more of the volatilized material.

Investigations of "The Moisture Content of Some Typical Coals," by G. A. Hulett, E. Mack, and C. P. Smyth (*Amer. Jour. Sci.*, 43, 1917, pp. 89-110, and 45, 1918, pp. 174-84) have clearly shown the existence of a critical decomposition temperature, varying with the coal type, at which "synthetic water" makes its appearance, in distinction from the free moisture and that held as a condensed film on the surface of colloidal coal particles. These temperatures are in the neighborhood of 250° C.

This mixture of volatilized products, high in oxygen-containing substances, passes, in the main, through the layers of coking material at gradually increasing temperatures, acquiring increments of hydrogen, hydrocarbons, CO and water vapor, the last-named constituent still remaining a prominent one. The hydroxyl-bodies of the tar become altered in this intermediate stage, under the influence of the somewhat higher temperature, and their oxygen reacts with oxydizable materials. Such reactions of oxidation in the intermediate stages of carbonization may account for exo-thermic phenomena noted in these stages by Parr and others.[2]

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[1] Horace C. Porter and F. K. Ovitz, "The Volatile Matter of Coal," Bulletin 1, Bureau of Mines (1910), pp. 28, 33, 35; O. Rau and G. Lambris, "Formation of Water in the Dry Distillation of Fuels," *Journal für Gas beleuchtung*, **56**, 533, 557, 589 (1913); S. W. Parr and H. L. Olin, Bulletin 60, University of Illinois Engineering Experiment Station (1912); S. W. Parr and C. K. Francis, Bulletin 24, University of Illinois Engineering Experiment Station (1908); M. J. Burgess and R. V. Wheeler, *Trans. of the Chemical Society* (London), **105**, 132 (1914).

It is, in any event, worthy of note that water vapor and oxygenated bodies exert a large mass-influence on the reactions occurring in the early stages, probably up to 700° C. Whether the final yields of hydrocarbons and the important combustibles of gas and tar are materially affected by such influence, is open to question; but it is certain that the presence of these bodies tends to protect ammonia and certain valuable light oils from decomposition, and that greater yields of those products are obtained from the higher-oxygen coals.

The Constitution of Coal. In the study of the phenomena of coal carbonization and the reactions occurring therein, it is of importance to know the nature of the material undergoing decomposition and in what constitutional respects the various types of coal differ from each other.

Coal has proven difficult of analysis in this way. The substances that comprise it are hard to identify. Research, in vast amount, painstaking and well-organized, has been applied to the problem, but has led thus far only to an approximation, a classification of the materials present into groups having certain characteristics.

It cannot be said with certainty, for example, that hydrocarbons, in more than traces, are present in coal, or that there is free elemental carbon. It appears likely that the latter is not present. Coal does not go into solution appreciably in the ordinary solvents, and identification tests, therefore, through that medium are almost impossible to apply. When so-called solution is obtained in special or unusual solvents, such as phenol or pyridene, by the aid of heat or pressure, there can be no certainty that decomposition or depolymerization has not occurred, before any constituent can thus be recovered for identification.[3]

The action of saponifying and hydrolyzing reagents (alkaline hydroxides) on the substances of coal is inappreciable, and indicates, therefore,[4] the unlikelihood of the presence of hydroxyl or carboxyl groupings.

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[2] S. W. Parr and T. E. Layng, *Journal of Industrial and Engineering Chemistry,* 13, 14-17 (1921); S. W. Parr, *Trans. of the Illinois State Academy of Science,* Vol. 15, 342-358; S. W. Parr, *Gas-Age Record,* 50, 531-4 (1922); H. Hollings and J. W. Cobb, "Thermal Study of the Carbonization Process," *Journal of the Chemical Society* (London), 107, 1106-1115 (1915).

[3] F. V. Tideswell, in *Fuel,* 2, 244-7 (1923), referring to the work of S. R. Illingworth, *Fuel,* 213-9 (1922), on the action of solvents on coal, states that pyridene, in its action on coal, exerts more than a mere solvent action and more than depolymerization. It is likely that it decomposes the insoluble component to form a series of soluble compounds, splits off a simple soluble compound from a complex insoluble one, leaving a still complex insoluble residue, and causes a mechanical resolution of various morphological entities of coal into smaller aggregates, giving access by the solvent to previously protected soluble material.

There appears to be an agreement among investigators that coal is a conglomerate of many different substances. These substances can be grouped in classes having, in some degree, like characteristics but their chemical nature, up to the present time, is only surmised.

Some of the investigators have held [5] that there can be distinguished in coal two classes of substances behaving differently under decomposition by heat. One, it is held, is easily decomposable by temperatures below 700° C. and yields thus chiefly the paraffin hydrocarbons; the other decomposes only with difficulty below 700° C. and yields, above that temperature, chiefly hydrogen with oxides of carbon. This view as to a distinct characterization of classes of material present, by behavior in decomposition, has not been generally accepted, and in fact has been modified [6] in a measure by the proponents.

It appears probable that essentially *all* of the substances present in coal decompose easily by heat, at temperatures between 250° and 450° C.[7] and that their first decomposition products, in the aggregate, consist of water, oxides of carbon, gaseous paraffins and liquid hydro-aromatic, alkyl-aromatic, and phenolic bodies. Some hydrogen, also, is probably formed in this early stage.

The large evolution of hydrogen, accompanied by CO and CH_4, at an *apparent* "critical" temperature, near 700°-750° C., is, in all probability, to be ascribed to a second stage of decomposition, becoming rapid at that temperature, in the partially carbonized solids, and the thermal decomposition of higher paraffins and hydro-aromatics in the early volatile matter. The phenomenon does not evidence the original presence in the coal of a constituent characterized by initial decomposition at that temperature and so as to produce hydrogen in large amount.

The Microscopic Character of Coal. Largely from the paleobotanic standpoint, coal has been carefully studied microscopically. The object has been chiefly to trace its origin, through the evidence of the plant remains still recognizable to the expert in paleo-botany. Little has been gleaned of a chemical nature, or that leads directly to a knowledge of the present chemical or morphological make-up of the coal substance.

Evidence has been found, however, that coal has resulted from the degradation of plant tissues, wood, twigs, leaves, etc., through the medium of the peat bog, and by decay due to bacterial action, accompanied or followed by pressure (*not* probably also by high heat).

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[4] D. T. Jones and R. V. Wheeler, *Trans. of the Chemical Society* (London), **109**, 712 (1916).

[5] M. J. Burgess and R. V. Wheeler, *Trans. of the Chem. Soc.*, **99**, 649-667 (1911), and **105**, 131-140 (1914); D. T. Jones and R. V. Wheeler, *Trans. of the Chem. Soc.*, **105**, 140-51 (1914).

[6] M. C. Stopes and R. V. Wheeler, Monograph on The Constitution of Coal, (British) Department of Scientific and Industrial Research, 1918, p. 12.

[7] G. B. Taylor and Horace C. Porter, "The Primary Volatile Products of the Carbonization of Coal," Technical Paper 140, Bureau of Mines, 1916, pp. 42-43.

There is shown no conclusive evidence of the presence of a "fundamental coal jelly." The opinion is favored commonly, among investigators, that "the mass of coal is formed of plant tissues very considerably preserved in their original form, partly also considerably broken down, and locally so broken down as to form what may be termed a jelly or fine pulp, but even in this, though the plant cells are fragmented, they retain in part somewhat of their original chemical structure and in part are reduced to various 'ulmic' compounds."[8] The "ulmic compounds," so-called, are of undetermined constitution, but are supposed to have resulted from the degradation of cellulose, and at one stage in their development, viz., as they occur in decayed wood, peat and lignite, are characterized by a kind of solubility in alkaline solutions. This soluble form, however, does not occur in coal. They are indefinitely referred to sometimes as "humus" or "humic substances."

The discovery, microscopically, of "resinous" and "cellulosic" bodies in coal, has been freely claimed, but is to be set down still as veiled in an uncertainty, arising from confusion of the meaning of these terms. Indications of the occasional occurrence of well-characterized and unaltered resins have been noted.

The conclusions from microscopic studies of coal cannot be detailed here. Many excellent memoirs on the subject have been published, and the reader is referred especially to that of White and Thiessen,[9] American investigators and pioneers in this field, also to that of Stopes and Wheeler[10] (British), wherein a comprehensive review of the subject of the Constitution of Coal and its literature is embodied.

By way of summary of the state of knowledge on the subject in 1918, Stopes and Wheeler (*loc. cit.*, p. 41), conclude their thorough analysis and review with the following paragraph:

"Summing up those modern researches which seem to us to be the best founded, . . . coal is a conglomerate of morphologically organised plant tissues, natural plant-substances devoid of morphological organisation (such, for instance, as 'resin'), together with the degradation products of a portion of the plant tissue and cell contents comminuted, morphologically disorganised, or present in the form of varying members of the ulmin group. . . . Coal, therefore, contains compounds of a richly varied nature, many (perhaps the greater number) of which are not merged and resolved at haphazard through the coal substance, but cohere to maintain the very morphological structures in which they originally took rise. . . . The subtlety and complexity of the substances present in coal is beyond present technique to unravel, but more can be hoped for than the first very rough separation into alpha, beta, and gamma substances. Where individual tissues or identifiable parts can be isolated, the resulting products of which they are the source should be determinable. Then, fraction after fraction, the nature of each portion of the opaque coal mass may be made clear."

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[8] Marie C. Stopes and R. V. Wheeler, Monograph on the Constitution of Coal, Department of Scientific and Industrial Research (Great Britain), 1918, p. 32.

[9] David White and R. Thiessen, "The Origin of Coal," Bulletin 38, Bureau of Mines, 1913; R. Thiessen, Structure in Paleozoic Bituminous Coals, Bulletin 117, Bureau of Mines, 1920.

[10] *Loc. cit.*

Theories of the Chemical Structure of Coal. As has been noted, direct evidence of the chemical nature of coal is still lacking. There has been secured, however, a large amount of experimental data, largely through carbonization studies, which may advantageously and legitimately be used to develop hypotheses of the chemical composition. Such theories have been proposed by D. T. Jones and R. V. Wheeler [11] on the basis of a furane group (five-membered) resulting from cellulose degradation, as a characteristic linking unit between other groups; F. Fischer and H. Schrader,[12] who discern the probability of an analogous structure in coal to that of lignin, viz., cyclic groupings, with six-membered rings, and side-chain linkages resulting from condensation of the acetyl, methoxyl, and other groups of lignin and the off-splitting of water and CO_2 therefrom; Jerome J. Morgan and R. P. Soule,[13] who, on the basis of studies of low temperature tars, and the fact that they find them almost entirely cyclic in nature, made up of six-membered rings or combination thereof, have developed a six-membered ring "mosaic" theory. This they express in summary as follows:

"The chemical properties of coal," it is suggested, "may be represented by a structure containing many such cycles" (six-membered). "This structure may be pictured as an aggregate of 'mosaics' of these rings. Some of the mosaics contain oxygen, and display the insolubility characteristic of the 'cellulosic degradation products' (noted by Jones and Wheeler) or, according to Fischer and Schrader 'the lignin degradation products.' These may be regarded as polymerized phenols, . . . or as multi-molecular structures in which component rings are joined together by oxygen-containing bridges. Heating results in the breaking of these bridges with the formation of high-boiling phenols, the side-chains of which are remnants of other broken linkages.

Similarly other mosaics may be pictured to represent the same typical rings held together by bridges of paraffin hydro-carbons, the breaking or detachment of which are responsible for the presence of straight-chain hydro-carbons in low temperature tars (compare the 'bound molecules' of Jones and Wheeler), . . . These structures are more soluble and have been called the 'resinous constituents'" (by Wheeler and associates). "Nitrogen and sulphur compounds may be regarded as appearing in strictly analogous configurations."

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[11] *Journal of the Chemical Society,* 105, 140 and 2462 (1914); 107, 1318 (1915); 109, 707 (1916).

[12] *Brennstoffe-Chemie,* 2, 37 and 237 (1921).

[13] "Studies in the Carbonization of Coal: The Mechanism of Coal Carbonization," *Chemical and Metallurgical Engineering,* 26, 1025-30 (1922).

The Mechanism of Coal Carbonization.

Physical Aspects. To the casual observer, it is generally not clear how composite and diversified is the physical character of the process of coal carbonization. This is illustrated by frequently occurring descriptions of carbonizing operations as taking place at a single definite temperature.

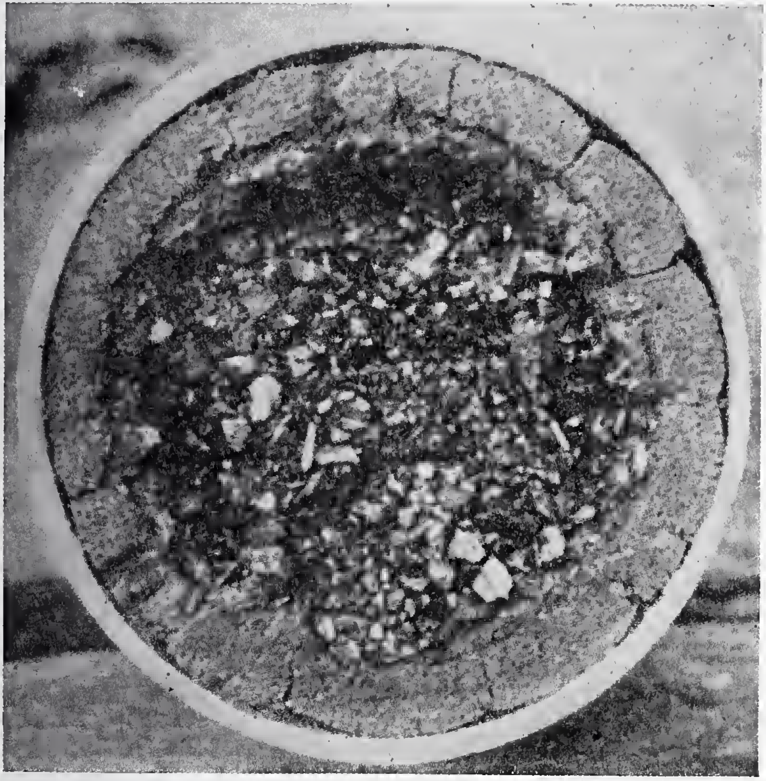

FIG. 12.—Cross Section of Coal Charge Partially Coked in a Vertical Gas Retort. Early Stage. (Photograph reprinted by courtesy of O. B. Evans, and the American Gas Association.)

As a matter of fact, in any process of coal carbonization, all temperatures, from that of the outer air to the maximum of the heated wall, exist in the carbonizing mass, during a large part of the period of carbonizing. The center of the mass does not reach its maximum until near the end of the period. (In some processes of coal carbonization, wherein the coal is mechanically agitated, the temperature gradients are much less marked.)

This condition of variant temperatures establishes the important co-related condition of variant reactions among gases, vapors and solids in the carbonizing mass. The condition persists throughout the period.

We have then, in so-called "high temperature" carbonization a combination of low-temperature and high-temperature conditions. Low-temperature carbonization proceeds in a zone in the interior of the mass (a contracting ring of narrow cross-section as will be shown later), and the products thereof, liquid, gaseous, and solid, then are subjected to higher-temperature conditions, these stages being distinct and of considerable duration of time. The primary, or "near-primary" products of the early, low-temperature, processes, the solid residue and the volatilized parts, continue their decomposition and molecular rearrangement, under the influence of the higher temperatures.

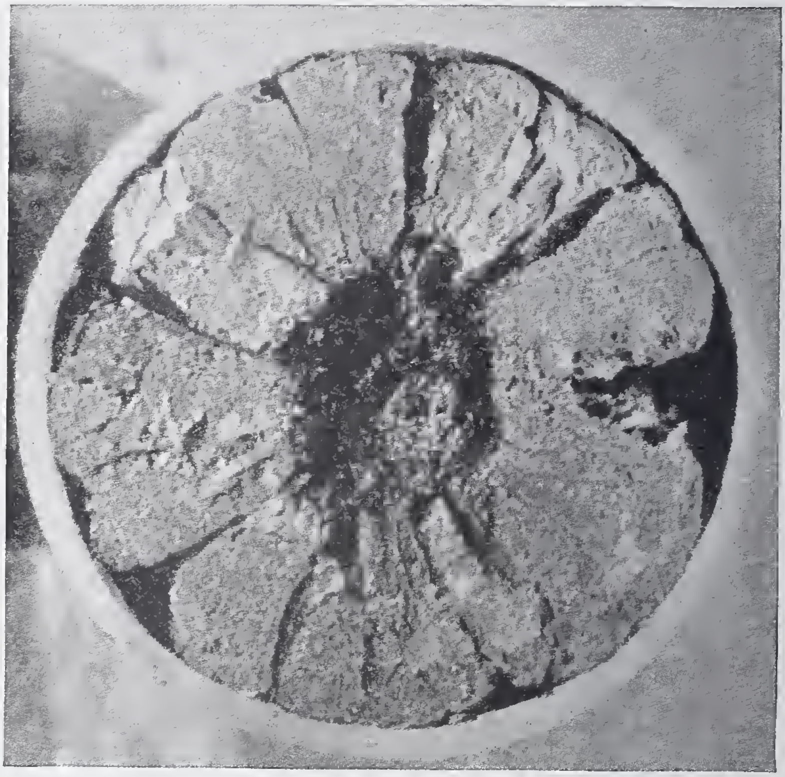

Fig. 13.—Cross Section of Coal Charge Partially Coked in a Vertical Gas Retort, Middle Stage. (Photograph reprinted by courtesy of O. B. Evans, and the American Gas Association.)

It is doubtful whether or not coal melts without decomposition. Unquestionably most bituminous coals soften or become plastic when heated to a temperature between 300° and 400° C., but decomposition, with most coals, whether coking or non-coking, appears to have begun coincidently with the softening. (See further on this, pp. 93-4.)

In the charge of an oven or retort, a plastic layer or zone, thin, but very difficultly permeable to gases, moves slowly in a contracting ring toward the center. On the inner side of the ring is raw coal, hardly, if at all, higher in temperature than that of boiling water. Outside of the plastic layer, toward the source of heat, lies material in a state of decomposition, no longer coal, but intermediate between coal and coke. It becomes solid, at the edge of the plastic zone, where, in the semi-solid transition stage, it has been rendered porous by the escaping gases. The cell walls in this material are thickened by deposition of carbon or carbon-nuclei from decomposing gases, and become hardened and strengthened by the higher heating which follows. The bearing of these steps on the relative coking properties of different coals is explained in later paragraphs.

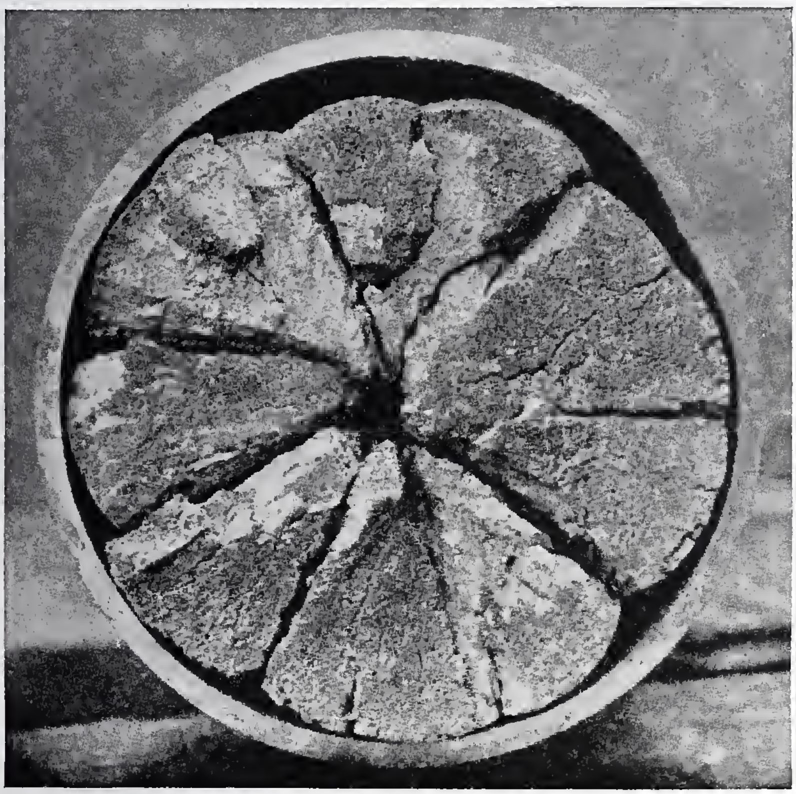

Fig. 14.—Cross Section of Coal Charge Partially Coked in a Vertical Gas Retort, Final Stage. (Photograph reprinted by courtesy of O. B. Evans and the American Gas Association.)

Illustrations (Figures 12-14), not drawn from theory, but reproduced from photographs of partially coked charges in a vertical gas retort, have been presented by O. B. Evans[14] as showing the progress of coking at successive stages, and the presence of the plastic ring

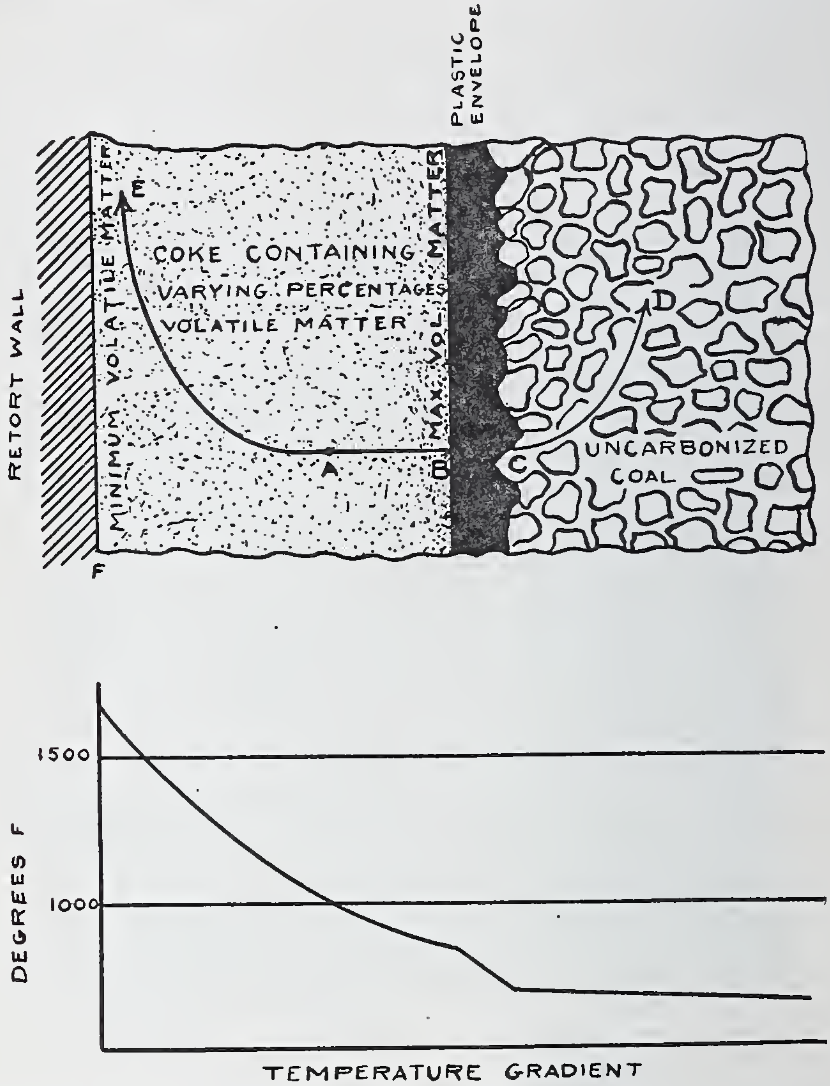

Fig. 15.—Diagram Illustrating the Progress of Carbonization in a Coal Charge and the Position of the Plastic Ring. (Reproduced by courtesy of O. B. Evans and the American Gas Association.)

(also Figure 15). The theory of the progress of carbonization in an oven or retort is explained also in detail by W. H. Fulweiler.[15]

In Figure 45, facing page 154, is shown the theoretical progress of coking in a battery of ovens, based on determinations of temperatures at different points in the charge at successive intervals.

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[14] Some Notes on the Carbonization of Coal in Vertical Retorts, Proceedings Amer. Gas Institute, 1913.

[15] Physical Theory of Coal Carbonization, Proceedings Amer. Gas Institute, 1908, 637.

The Path of Gas Travel. There has been some difference of opinion on this important phase of the physical process of carbonization. O. B. Evans[16] has concluded from measurements of pressures and analyses of gas samples drawn from the inner zones in a vertical retort, that part of the gas passes up through the cool core of uncoked coal in the center of the charge, but a much greater portion ascends through the less resistant coke and semi-coke in the region outside of the plastic zone. He also notes that a pressure differential of as much as 30 inches of water may exist between the inner and outer sides of the plastic zone.

It is reasonable to suppose that the gases will take the path of least resistance. Those that are generated at low temperature in the plastic zone probably in part pass out through the inner core, and a small part even of the gas from high-temperature secondary decomposition—perhaps part of what is formed near the bottom of the oven or retort—may penetrate the plastic layer, owing to pressure conditions, and pass out by way of the core. But the great bulk of the gas, being generated in the regions at 700° C. or higher, outside of the plastic zone, passes out through the coke and along the fissures therein, owing to the resistance offered by the plastic layer. Considerations, however, based on relative compositions of the gas from horizontal and vertical retorts lead to the belief that below the surface of the coal charge, less of the gas moves in actual contact with the hot wall than passes through the zones of semi-coke where the temperatures are lower than at the wall.

Loss of Heat in the Escaping Gases. A large proportion, perhaps 40 per cent., of the heat which is introduced through the walls of the high-temperature carbonizing retort to effect the coking process, passes out in the sensible and latent heat of the vapors and gases. It would be advantageous to recover all or part of this heat by utilizing it to preheat the raw coal, in effect to use the raw coal as condenser and economizer. In the continuous vertical retort, this is done in a measure, since the issuing gas in part traverses the upper sections of the retort which are kept filled with fresh coal continuously moving downwards.

There have been proposals also to draw by suction the gases and vapors away from or through the plastic layer into the inner core, and out by way of an exit pipe placed in the center of the charge.[17] Some of the gas from the hotter zones would be withdrawn through an outlet in the top of the retort.

These proposals are, in many respects, rational, since they permit recovery not only of the heat of the gases but also of by-products in the form of oils and rich gases, otherwise (in the usual coking processes) degraded disadvantageously into carbon, pitch and gas. It remains to be seen whether certain practical working difficulties encountered in the application of such methods of gas withdrawal can be overcome.

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[16] *Loc. cit.;* also, same, in *Amer. Gas Light Jour.,* 99, 338 (1913).

[17] The Wallace Low Temperature Retort, described in Reports of Carbonization Committee, American Gas Association, 1922 and 1923; patented by G. W. Wallace, Canadian Pat. 189,426; A. W. Warner, "A Study of Some Physical Laws Governing Coal Carbonization," *Amer. Gas Assoc. Monthly,* 5, 437 (1923).

Chemical Aspects of the Mechanism of Carbonization. The process of carbonization may be considered as taking place mainly in three steps, each involving its own set of reactions and influences: (1) the primary breakdown at low temperatures liberating liquids, some gases and a solid residue; (2) secondary reactions among these liberated tars and gases by higher temperatures, involving both degradation and synthesis; and (3) further progressive breakdown of the solid, producing chiefly gases and a hard carbonized residue. In all coal carbonization, as practically carried out, these steps are proceeding, in adjacent sections, simultaneously.

Undoubtedly, condensable vapors, giving thin tars or oils, are the principal ingredient of the low-temperature, early-volatilized product. These pass mainly into the region of secondary decomposition, where they mingle with the gases that are being set free (in relatively greater volume) from the semi-coked solids, and the mixture then—at increasing velocity—moves out through the hot mass of coke and semi-coke to the free space above the charge.

There is, accordingly, in this reacting mixture, a widely varying percentage of hydrogen, becoming large as the gases approach their outlet, but always exercising an influence on the chemical equilibria in reactions. Water vapor, as has been previously mentioned, is also at all times present in important percentage, so as to influence the course of reactions.

Chemically the early-formed products (as volatilized) are made up, as has been elsewhere outlined, of water vapor, complex hydrocarbons (of cyclic hydro-aromatic and alkyl-aromatic nature), hydroxy- or phenolic compounds, nitrogen bases, hydrogen-sulphide and some hydrogen. The hydrocarbons easily break down into simpler structures—which in turn if they have unsaturated bonds, may, at high temperatures, synthesize ring-formed bodies in the final tars and gases.

Some investigators consider it doubtful that synthetic formations play more than a minor rôle in the secondary reactions of carbonization.[18] It appears likely that the temperatures to which the reacting mixtures are subjected, while passing through the coke and semi-coke of a charge, are not sufficiently high to effect pyro-genetic syntheses in a large degree. In the hot free space, however, of horizontal gas retorts, where exists an atmosphere high in hydrogen, syntheses may occur in important measure.

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[18] J. J. Morgan, *Chemical & Metallurgical Engineering*, 26, 1025-1030 (1922), especially summary on p. 1030.

These questions are treated in detail by Wm. A. Bone[19] in his thorough and masterly exposition of the reactions of coal carbonization. Professor Bone concludes there is good reason to believe that pyrogenetic syntheses of ring-formed hydrocarbons through the medium of ethylene ($CH_2 : CH_2$) play an important part in the final result of high temperature carbonization.

In another chapter herein (Chapter 11, pages 320-335) the genesis of some of the constituents of tars, light oils and gas is traced.

Commercially the reactions tending to increase production of ammonia, benzene and toluene, and simple permanent hydrocarbons in the gas, and lessen the severe degradation of early-formed hydrocarbons into carbon, heavy multiple-ring bodies, and pitch, are of greatest moment for immediate practical elucidation.

As to nitrogen compounds and the theory of their behavior in coal carbonization, supported by experimental evidence in considerable measure, a summary is presented in Chapter 6, together with an outline of the behavior of sulphur. These two classes of compounds, the former, nitrogen bodies in particular, constituting a considerable part of the original coal substance—have a large commercial importance in carbonization, and are worthy of special consideration.

Theory of the Coking Property. The elusive property, varying among different kinds of coal, of producing strong well-formed coke, has not as yet been given a definite explanation, established by direct evidence. A vast amount of investigation has been applied to the problem, and while progress has been made and much experimental data accumulated which eventually will be of service in draughting the true explanation of this important property, the characteristic principle or ingredient which imparts the coking property has not yet been determined.

V. B. Lewes,[20] R. V. Wheeler,[21] and recently S. R. Illingworth[22] have taken the lead in attributing the coking property to so-called "resinous" constituents extractable by pyridene. It appears to be well-established that a coal residue remaining after extraction with pyridene, or with phenol, does not coke, and that by re-mixing the residue and extract the coking property is restored.

Slow oxidation has been shown to destroy the coking property. Heating at low temperatures to the stage of incipient fusion, cooling, and pulverizing, leaves an altered material which on reheating does not coke. Lignites, sub-bituminous and a few bituminous coals show practically no coking power. The bituminous coals which do coke vary widely in the quality of the coke made.

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[19] "Coal and Its Scientific Uses," Longmans, Green & Co., London, 1919, especially Chapter 8.

[20] Vivian B. Lewes, "The Carbonization of Coal," Benn Bros., Ltd., London, 1918, page 24.

[21] Summary of researches, *Fuel*, **2**, 29-41, 83-92 (1923); see also Burgess & Wheeler, *Trans. of the Chemical Society*, **99**, 649 (1911), and **105**, 131 (1914).

[22] S. Roy Illingworth, *Jour. Soc. Chem. Ind.* **39**, 111 and 133 (1920).

It is hardly a sufficient explanation of the coking property to assume that substances, extractable by certain solvents, impart the property when present in sufficient amount. The nature of the action of these coking ingredients demands explanation. Furthermore, coke, whether made at low temperatures or high, appears sufficiently homogeneous to preclude any idea of the sticking together of non-coking ingredients by a fusible "cementing" material. Coal fused at 400° C. and cooled, appears as an expanded spongy mass fused in its entirety and with uniformity. The term "cementing" used to describe ingredients of coal appears unfortunate.

S. W. Parr, in studies of the coking of the Illinois type of coal[23] has determined certain effects of oxidation on the coal and on its ingredients separately, which indicate that the coking property involves factors of greater complexity than the mere presence of a binding material. He has separated the ingredients soluble in boiling phenol from the insoluble non-coking residue. On re-mixing these ingredients the coking quality was restored. If, however, the insoluble non-coking residue was first oxidized to saturation and then re-mixed with the extracted material, the coking quality was *not* restored. Oxidation of the original coal destroyed the coking power, but not necessarily by alteration of the soluble so-called "resinic" constituents. It appears that oxidation of the insoluble constituents has a like effect in taking away the coking tendency.

We are led to conclude, therefore, that the coking property may rest possibly in an inter-action of the two classes of constituents or more probably in the fusion of the material as a whole, a "coking coal," on fusion, *producing* a material like molten-pitch or tar, which exudes and intumesces in the softened mass, and carbonizes in such manner as to form a strong coke. The fact of the extractability of a "coking constituent" may rest entirely on the depolymerization or decomposition of the coal substance into parts that behave differently in the tar-exuding property which makes coke.

The observation that prolonged heating at the fusion point destroys the coking property in a coking coal indicates that decomposition occurs at the fusion temperature, a fact opposed to the theory sometimes advanced that, to be of coking character, a coal must fuse *before* it begins to decompose.

Autogenous Coking of High-Oxygen Coals. S. W. Parr, with T. E. Layng and others, in investigations at the University of Illinois[24] has developed a process of coking the Illinois type of coal at a maximum temperature of 700°-750° C. by the aid of autogenous heating in the interior of the charge due to exothermic reactions of the oxygen-bearing constituents in the coal.

[23] *Trans. Illinois State Academy of Science,* Vol. 15, pp. 342-358, especially pp. 352-4.

[24] *Jour. of Industrial & Engineering Chem.,* 13, 14-16 (1921); *Trans. Illinois State Academy of Science,* Vol. 15, pp. 342-58, especially pp. 354-58; *Gas Age-Record,* 50, 531-4 (1922).

By preheating of the charge to 300° C. in a separate vessel, preferably rotating so as to facilitate thorough heating of the entire mass of coal to that temperature, or "slightly below the point of active decomposition," and then placing the preheated charge in the retort at 700° or 750° C., it is claimed that the exothermic reactions prominently appearing in such coals *at that stage* in their decomposition, maintain a rapid progression of the coking through the mass, and improve greatly the density and strength of the coke formed.

Coke of excellent quality for many purposes has thus been made by these investigators from Illinois coals, working on a semi-commercial scale.

Hydrogenation of Coal under Pressure. Of great interest in connection with the subject of the constitution of coal is the work of F. Bergius[25] in the liquefaction of coal mixed with heavy mineral oil, by treatment with hydrogen at 400° C. under 40-200 atmospheres' pressure. By distillation of the product and repeated re-hydrogenation of the residue a large percentage (up to 60 per cent.) of the coal has been converted to low-boiling oils. The process has been put on a commercial scale in Germany.

There is indicated hereby the presence of substances in coal with unsaturated bonds capable of taking on hydrogen to form readily detachable side-chain groups, which separate on distillation. A relatively large proportion of such side-chain groupings present in the coal substance also is indicated. Coal of more than 85 per cent. carbon content has not been successfully treated.

Investigations of coal distillation under pressure, by J. H. Capps and G. A. Hulett, *Journal of Industrial and Engineering Chemistry*, 9, 927-35 (1917), show increase of low-boiling compounds in the condensable vapors, particularly of aromatic substances. They find also up to 600° C. an increase in the volume of gas, with rise in pressure under which carbonization takes place.

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[25] F. Bergius, "New Methods for the Utilization of Mineral Oils and Coal," *Zeitschrift für angewandte Chemie*, 34 (Aufsatzteil), 341-7 (1921); U. S. Patent 1,342,790, June 8, 1920; J. I. Graham and H. G. Shatwell, "The Artificial Production of Coal and the Hydrogenation of Coal and Oil," *Fuel*, 2, 54-7 (1923), (a description of the past and new work of Bergius). Anon., *Iron & Coal Trades Review*, 107, 735 (1923).

Chapter 6.

Nitrogen and Sulphur Compounds in Coal, Their Behavior in Carbonization.

General. Owing to the commercial importance of ammonia, a knowledge of the behavior of the nitrogen compounds in coking is of especial value to the carbonization industry. Sulphur also, since it is objectionable as a constituent either of gas or coke, requires careful control. The study of its behavior, therefore, in carbonization of coal and its forms of combination in the products, is industrially important.

The nitrogen of coal is quite generally attributed [1] to the presence of degradation products of the vegetable proteins.

It is estimated by Bone (*loc. cit.*) that on this basis the content of nitrogenous compounds in coal may reach about 10 per cent. but not higher. Bone states also that the proteid origin of the nitrogenous constituents accounts, as well, for the occurrence of "organic" sulphur in coal.

Forms of Nitrogen Combination.

It has been suggested [2] with support of experimental evidence that two forms of nitrogen compound are present in coal, one, in small amount, of an amino nature easily decomposed by heat, the other ring-formed, probably of the five-membered pyrrol type, but highly complex and polymerized, and very stable until heated to a high temperature.

The former compound is thought to produce volatile nitrogen bases passing mostly into the tar. Certain investigations [3] of low temperature tars have discovered 0.624 per cent. of nitrogen bases, by weight on the crude dry tar, and have shown these to be made up of 80 per cent. tertiary bases, 20 per cent. secondary and no primary.

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[1] E. Terres, "Studies of the Combination of Nitrogen in Coal and Coke," *Journal für Gasbeleuchtung,* 59, 519-21 (1916) (proposes, not vegetable proteids, but animal, as the probable origin); Wm. A. Bone, "Coal and Its Scientific Uses" (London, 1919), pp. 76-78; M. C. Stopes and R. V. Wheeler, Monograph on the Constitution of Coal, Dept. of Sci. and Ind. Research, London, 1918, p. 14; J. Harger, *J. Soc. Chem. Ind.,* 33, 389-92 (1914); Vernon Bosman (with S. W. Parr), "The Investigation of Certain Types of South African Coals, with Special Reference to Their High Nitrogen Content," *So. African Journal of Industries,* May, 1923.

[2] By J. Harger, *loc. cit.,* and by V. Bosman (with S. W. Parr), *loc. cit.*

[3] J. J. Morgan and R. P. Soule, *Chem. and Metallurgical Engineering,* 26, 923 and 977 (1922).

These bases were found to have densities and molecular weights which indicated partly hydrogenated nuclei and the presence of side chains of considerable length.

The stable ring-formed nitrogen compound begins slowly to decompose at 550°-600° C. yielding ammonia, but the ammonia formation is not rapid until 700°-750° is reached. Much of the nitrogen in this compound (50-60 per cent.) remains fixed in the coke residue—unless liberated by steam at high temperatures, and its stability in this condition has led to a suggestion [4] that in coke the nitrogen exists as a nitride of carbon.

Most cokes (by high temperatures) contain from 0.7 per cent. to 1.2 per cent. nitrogen, and whether in the form of nitride of carbon or a ring-formed carbon-nitrogen nucleus, the state of combination is remarkably stable. Treatment with steam or hydrogen at high temperature effects decomposition and forms ammonia, but little or no breakdown can be induced by heat alone.

The Mechanism of Ammonia Formation. Ammonia is not formed appreciably below 500° C. in the coal. Its maximum formation under usual coal carbonizing conditions is at about 850° C., part, however, of the recovery here being due, no doubt, to secondary reactions such as those of hydrogen and steam on the residual solid.

The bulk of the ammonia, possibly all, comes from decomposition of the complex polymerized nitrogen-carbon ring compounds, probably little or none of it from the easily-decomposed amino derivatives.

A part only of the nitrogen held in this ring-form combination is liberated, the amount set free by heat alone being uncertain. Some of it is liberated by the aid of steam and hydrogen arising from carbonization. When no auxiliary steam or gas is introduced, 50-60 per cent. of the original nitrogen remains fixed in the coke. Whether all of the balance, viz., 40-50 per cent., is liberated first as ammonia which then suffers thermal decomposition in part into free nitrogen, or whether some free nitrogen is formed directly by decomposition of the coal substance, remains uncertain. In high temperature carbonization, at all events, 18 to 30 per cent. of the original coal nitrogen is found in the free nitrogen of the gas, and 12 to 22 per cent. is recovered as ammonia.

Unquestionably, as researches by Monkhouse and Cobb, Hodsman and others [5] have demonstrated, ammonia undergoes thermal decomposition under the conditions of the coke oven and gas retort. The amount of such decomposition may be slight under some conditions,

[4] M. G. Christie, Inaug. Diss., Aachen, 1908.

[5] A. C. Monkhouse and J. W. Cobb, *Gas Journal* (London), 156, 334-40 (1921); H. J. Hodsman, *Gas World*, 76, Coking Section, 10-14 (1922); R. A. Mott, *Gas World*, 78, Cok. Sect., 12-17 (1923); also *Colliery Guardian*, 125, 578-9 (1923); R. A. Mott and H. J. Hodsman, *Jour. Soc. Chem. Ind.*, 42, 4-12T, 26T, 39-40T (1923); H. D. Greenwood and H. J. Hodsman, *Jour. Soc. Chem. Ind.*, 41, 273-9T (1922); *Gas Journal*, Mar. 21, 1923, p. 750; A. Thau, *Brennstoffe-Chemie*, 1, 52 (1920).

but is of importance under others commonly occurring. For example, at 800°-900° C. the admission of small amounts of oxygen to the retort gases, or the passage of the gases over heated surfaces containing iron-oxide (unless these are coated with carbon), may decompose the ammonia in the gas to the extent of 10 to 25 per cent., especially if the gas be relatively dry. Steam in the gas tends not only to protect NH_3 already formed but to liberate more from the combined nitrogen of the coke and semi-coke.

An investigation by Monkhouse and Cobb (*loc. cit.*) has shown the effect of hydrogen and that of steam upon the nitrogen of low-temperature (500° C.) coke. Some of the results of this investigation were as follows:

TABLE II.

Coal Composition		500° Coke
Volatile matter	33.96 per cent.	Yield 70.0 per cent.
Ash	4.66	
Ash-free:		
Carbon	81.44	89.30 per cent.
Hydrogen	5.62	3.29
Nitrogen	1.86	2.03
Oxygen and sulphur	11.08	5.38
	100.00	100.00

On heating 500°-coke in hydrogen, successively at 600°, 800° and 1,000° C., Nitrogen balance:

		Per cent. of Original Coal Nitrogen
Liberated, in various forms, during coking		21.6 per cent.
Obtained as NH_3 by passing of hydrogen,		
At 600° C.	9.8	
At 800° C.	15.9	
At 1,000° C.	1.1	
		26.8
Left in coke		22.1
Liberated as free nitrogen		29.5
		100.0

On heating 500°-coke at 800° C. in an atmosphere of nitrogen and steam successively:

Nitrogen balance:

Liberated, in various forms during coking		21.6 per cent.
Obtained as ammonia,		
By passage of nitrogen	8.4	
" " " steam	54.6	63.0
Unaccounted for (liberated as free nitrogen),		
During passage of nitrogen	15.3	
" " " steam	0.1	15.4
		100.0

(Coke reduced to ash.)

Nitrogen Distribution during Carbonization. The general average distribution of nitrogen stated in a previous paragraph (page 97) is based on the reported results of actual determinations and the known yields of ammonia in average coke oven and retort practice. As explained, the results vary according to temperature in the oven tops and other conditions. In modern coke ovens and continuous vertical retorts (without steaming) yields of 5.0-7.5 pounds of NH_3 per ton of coal may be expected, according to the type of coal used and the conditions. This is usually equivalent to 13-20 per cent. of the total original nitrogen.

In a British plant of coke ovens of the Otto-Hilgenstock type, experiments by Short[6] in 1907, using Durham (England) coal gave distribution of nitrogen as stated below; and in modern intermittent vertical retorts at Rochester, N. Y., operated at 2,300° F. bottom temperature and 1,600° F. top temperature, with heated free space above the charge, C. H. Stone[7] reports the results of a 12-hour test as showing the distribution given below.[8]

TABLE 12.

NITROGEN DISTRIBUTION AS DETERMINED IN OTTO COKE OVENS (BRITISH PLANT) AND IN INTERMITTENT VERTICALS.

	Coke Ovens (British) (Short)	Intermittent Verticals (Stone)
Per cent. of total coal nitrogen obtained as ammonia..	15.16	13.05
" " " " " " " cyanides ..	1.43	1.42
" " " " " in tar	2.98	....
" " " " " " coke	43.31	46.30
" " " " " " gas (free)	37.12	39.23
	100.00	100.00
Total nitrogen, as per cent. of coal.............	1.57	1.75

Similar records are not at hand for horizontal retort practice, or for modern American by-product coke oven practice. The yields of ammonia, however, in the latter, are such as to represent a general average of about 17 per cent. of the nitrogen of the coal. In horizontal retorts, when small thin charges are used, the ammonia yields usually are such as to represent about 12-13 per cent. of the nitrogen of the coal.

In a laboratory carbonizing apparatus, Simmersbach[9] in 1914 investigated the nitrogen distribution in the carbonization of German coals at different temperatures. His results (Table 15) are of interest as showing the effect of the temperature of carbonization, but are not to be taken as indicative of the absolute yields of ammonia to be obtained in commercial installations.

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[6] A. Short, *Jour. Soc. Chem. Ind.*, 1907, p. 581.

[7] *Gas Age-Record*, 1923, pp. 241-3 (Feb. 24).

[8] Stone's results were reported in percentages of the total volatilized nitrogen, which was 0.94 per cent. out of a total of 1.75 per cent. in the coal; they are here converted, for the sake of comparison, to percentages of total nitrogen in the coal.

[9] O. Simmersbach, *Stahl und Eisen*, 34, 1155-59 (1914).

TABLE 15.

DISTRIBUTION OF NITROGEN (J. Simmersbach's Experiments, 1914).

(Taking as 100 per cent. the nitrogen content of the dry ash-free coal.)

A. *Upper-Silesian Coal* (1.396 per cent. N.).

(a) Size—1-1½ mm.

Temp. Deg. Cent.	As Ammonia. Per Cent.	As Hydrocyanic Acid. Per Cent.	In Tar. Per Cent.	As Free Nitrogen in Gas. Per Cent.	In Coke. Per Cent.
500	8.80	0.25	1.12	18.15	71.69
700	14.13	0.56	5.06	11.18	75.43
800	22.22	0.87	5.47	10.73	63.06
850	23.06	1.00	5.70	10.37	61.10
900	21.11	1.19	4.12	10.14	58.40
1,000	23.13	1.25	4.33	21.63	49.06
1,100	25.09	1.30	5.77	30.51	41.30
1,200	22.81	1.40	2.22	45.10	28.43

(b) Size—6-10 mm.

Temp. Deg. Cent.	As Ammonia. Per Cent.	As Hydrocyanic Acid. Per Cent.	In Tar. Per Cent.	As Free Nitrogen in Gas. Per Cent.	In Coke. Per Cent.
850	25.77	1.12	3.50	15.87	55.96
900	24.13	1.21	3.47	20.82	54.30
1,000	22.03	1.25	3.30	23.79	48.87

B. *Westphalia Coal* (1.392 per cent. N.).

Size—1-1½ mm.

Temp. Deg. Cent.	As Ammonia. Per Cent.	As Hydrocyanic Acid. Per Cent.	In Tar. Per Cent.	As Free Nitrogen in Gas. Per Cent.	In Coke. Per Cent.
800	19.46	0.76	1.90	5.88	71.98
850	22.14	1.00	1.77	4.98	70.05
900	19.34	1.11	1.60	5.00	67.58
1,000	19.00	1.25	1.87	21.54	55.73

C. *Lower Silesian Coal* (1.565 per cent. N.).

Size—1-1½ mm.

Temp. Deg. Cent.	As Ammonia. Per Cent.	As Hydrocyanic Acid. Per Cent.	In Tar. Per Cent.	As Free Nitrogen in Gas. Per Cent.	In Coke. Per Cent.
850	22.72	1.43	2.68	4.56	66.58
900	26.15	1.60	2.73	5.02	63.67
1,000	25.43	1.87	2.50	15.77	54.33

Summary. The breakdown of nitrogen compounds in coal carbonization is such as to volatilize only 40-50 per cent. of the nitrogen (without steaming), and a considerable part of the portion volatilized is free nitrogen. A small percentage is in organic compounds and cyanides and the balance (possibly 15 to 30 per cent.) in ammonia.

Part of this ammonia is decomposed by secondary thermal reactions, so that the final net yield is from 12 to 22 per cent.

The maximum possible increase of ammonia recovery by control of its secondary decomposition in the oven is perhaps 50 per cent. over present recovery. The practice of steaming has large possibilities of increasing yields.

A number of practical expedients for maintaining ammonia yields at a maximum are listed in Chapter 11, page 332.

The Sulphur Compounds Present in Coal, and Their Behavior in Carbonization.

Occurrence of Sulphur in Coal. The sulphur of coal may be present in any of three forms:

1. Organic sulphur;
2. Iron pyrites;
3. Sulphates.

The organic sulphur compounds in coal constitute what may be called the characteristic sulphur of the coal substance. They result from degradation of certain constituents of the original vegetable material—probably proteids,[10] and are combinations of sulphur with carbon, hydrogen, oxygen and nitrogen, of which the structure is not known. Investigations of the constitution of coal by means of the action of solvents have generally shown that each fraction thus separated contains sulphur. This fact may indicate that each of the many substances, or of the majority of them, making up the coal conglomerate, contains the sulphur atom in its molecule.[11]

The organic sulphur is inherent, not incidental, in coal, and, in the coal from any one well-characterized territory, it remains fairly constant in amount. In different coals (from various regions or beds) it may vary from 0.4 to 2.0 per cent.

Iron pyrite and marcasite (FeS_2) occur as incidental impurities in the coal beds, sometimes in finely-divided form, permeating the coal material (but not in chemical union with it), and again in solid massive lumps or in thin layers ("partings") laid down between sections of the coal bed. This form constitutes frequently the main portion of the sulphur present in coal, but may vary widely, from 0.1 or 0.2 per cent. to 7.0 or 8.0 per cent. (in coal as marketed, the amount in the coal bed being even greater in some cases).

Sulphates are also an incidental impurity and occur only in very slight amounts in the fresh coal as mined. They are formed by oxidation of the pyrite of the coal by weathering, the amount seldom exceeding in coal as used 10 per cent. of the pyritic sulphur present.

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[10] As suggested by W. A. Bone, *loc. cit.* Ed. Donath, *Brennstoffe Chemie,* 3, 1920-2 (1922), supports also this theory of the origin of the organic sulphur.

[11] M. C. Stopes and R. V. Wheeler, Monograph on the Constitution of Coal, Dept. of Sci. & Ind. Research (London, 1918), p. 13.

Methods of determination of the various forms of sulphur in coal by chemical analysis have been developed by A. R. Powell and others.[12]

The Behavior of Sulphur Compounds in Coal Carbonization. Powell[13] has made a thorough study, in a laboratory-sized carbonizing apparatus, of the manner of decomposition of the sulphur compounds of coal in carbonization. His apparatus was arranged so that the primary volatile products were swept out with a minimum of secondary decomposition. His conclusions are that under these conditions the primary sulphur reactions are:

(1) Iron pyrite decomposes, setting free exactly half of its sulphur as H_2S. When pyrite is heated alone, free sulphur is formed, but in the presence of coal under decomposition, all of the liberated sulphur forms H_2S.
(2) One-fourth to one-third of the organic sulphur is set free as H_2S, the balance remaining in the coke as a very stable carbon-sulphur combination. (This is reminiscent of the nitrogen behavior whereby a very stable carbon-nitrogen compound remains behind in the coke.)
(3) Sulphate sulphur remains in the coke, probably as a carbon-sulphur compound.

Secondary reactions, according to Powell, occur in the coke oven or gas retort,

(1) forming carbon bisulphide by the action of H_2S on red-hot coke (none of this compound being present in the primary products, or in those at low temperatures);
(2) liberating H_2S from the carbon-sulphur combination in the coke by action thereon of hydrogen in the gases of the coal decomposition processes.[14]

These conclusions of Powell's are supported in later investigations by others.[15]

The decomposition of sulphur compounds in coal takes place easily and at an early stage. The liberation of H_2S by primary decomposition is complete at 600° C. The secondary decomposition producing

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[12] S. W. Parr and A. R. Powell, "The Sulphur Forms in Coal," Bulletin 111, University of Illinois Engineering Experiment Station, 1919; Alfred R. Powell, *Jour. Ind. & Eng. Chem.*, 12, 887 (1920); also Bureau of Mines Technical Paper 254 (1921), "The Analysis of Sulphur Forms in Coal"; J. P. Wibaut, "Sulphur Compounds of Coal, Their Behavior on Distillation, and the Sulphur Compounds of Coke," *Brennstoffe Chemie*, 3, 273-8 (1922).

[13] Alfred R. Powell, "Coal Sulphur and Its Conversion in the Gas Retort," Amer. Gas Assoc., Techn. Sect. Sessions, Vol. 2 (1920), pp. 244-255.

[14] For further detail, see A. R. Powell, "The Desulphurizing Action of Hydrogen on Coke," *Jour. Ind. Eng. Chem.*, 12, 1077-81 (1920).

[15] J. P. Wibaut, *Brennstoffe Chemie*, 3, 273-8 (1922).

TABLE 14.

SULPHUR ELIMINATION IN COKING COALS IN BY-PRODUCT OVENS.

(After F. W. Sperr, Jr.)

State	County	Seam	Coking time, hrs.	Coke yield, per cent.	Sulphur			
					Per cent. in coal	Per cent. in coke	Per cent. of total eliminated	Per cent. of total retained
Colorado	Pueblo and Gunnison	....	21.5	74.0	0.68	0.57	38.0	62.0
Colorado	Pueblo and Gunnison	....	19.0	74.0	0.58	0.52	34.0	66.0
Colorado	Pueblo and Gunnison	....	19.5	73.0	0.51	0.47	32.7	67.3
Colorado	Pueblo and Gunnison	....	20.0	75.5	0.58	0.53	31.4	68.6
Colorado	Pueblo and Gunnison	....	18.0	73.0	0.58	0.54	32.0	68.0
Colorado	Pueblo and Gunnison	....	19.5	74.0	0.63	0.40	53.0	47.0
Alabama	Jefferson	....	18.0	75.0	0.99	0.84	36.4	63.6
Alabama	Jefferson	....	18.0	75.0	1.07	0.92	35.5	64.5
Alabama	Jefferson	....	18.0	75.0	0.99	0.99	25.0	75.0
Alabama	Jefferson	....	17.0	75.0	0.79	0.64	32.3	60.7
Alabama	Jefferson	....	18.0	75.0	1.39	1.17	36.8	63.2
Alabama	Jefferson	....	18.0	75.0	1.17	1.06	32.0	68.0
Alabama	Jefferson	....	18.0	71.0	1.25	1.23	30.2	69.8
Pennsylvania	Allegheny	Pittsburgh	20.0	70.0	1.12	0.84	47.5	52.5
Pennsylvania	Fayette	Pittsburgh (Klondike)	17.0	68.0	1.03	0.95	37.3	62.7
Pennsylvania	Fayette	Pittsburgh (Klondike)	19.0	68.0	1.03	1.00	34.0	66.0
Pennsylvania	Westmoreland	Pittsburgh	19.5	71.0	1.85	1.50	42.4	57.6
Pennsylvania	Washington	Pittsburgh	20.0	72.0	1.06	0.76	48.3	51.7
Pennsylvania	Fayette	Lower Kittanning	19.0	75.0	0.87	0.75	35.3	64.7
Washington	Pierce	No. 6	17.5	70.0	0.60	0.58	32.2	67.8
Washington	Pierce	Mostly No. 6	19.0	70.0	0.53	0.46	39.3	60.7
Washington	Pierce	No. 7	19.0	76.0	1.70	1.57	29.8	70.2
Washington	Pierce	No. 8	19.0	72.0	0.46	0.49	35.8	64.2
Washington	Pierce	No. 8	17.5	72.0	0.54	0.51	32.0	68.0
West Virginia	Preston	Lower Kittanning	17.5	70.0	1.84	1.56	40.6	59.4
West Virginia	Marion	Pittsburgh	16.5	68.0	1.48	1.56	28.3	71.7
West Virginia	Marion	Pittsburgh	16.5	68.0	1.62	1.63	31.6	68.4

MIXTURES WITH POCAHONTAS COAL

Illinois	20 per cent. Illinois + 80 per cent. Pocahontas	18.0	84.0	0.87	0.75	27.7	72.3
Pennsylvania	85 per cent. Pittsburgh (Allegheny Co.)	20.0	71.0	0.90	0.72	43.3	59.7
Pennsylvania	60 per cent. Pittsburgh (Allegheny Co.)	20.0	75.0	0.77	0.67	34.8	65.2
Pennsylvania	60 per cent. Pittsburgh (Allegheny Co.)	22.0	78.0	1.05	0.96	28.7	71.3

Sulphur Elimination in Coking Coals in By-Product Ovens.—*Continued.*

State	Mixtures with Pocahontas Coal	Coking time, hrs.	Coke yield, per cent.	Sulphur Per cent. in coal	Per cent. in coke	Per cent. of total eliminated	Per cent. of total retained
Pennsylvania	85 per cent. Pittsburgh (Fayette Co.)	21.0	71.0	1.07	0.81	46.4	53.6
Pennsylvania	70 per cent. Pittsburgh (Fayette Co.)	20.0	73.0	1.05	0.79	45.1	54.9
Pennsylvania	60 per cent. Pittsburgh (Fayette Co.)	20.0	73.0	1.03	0.76	46.2	53.8
Pennsylvania	30 per cent. Pittsburgh (Fayette Co.)	18.0	84.0	0.79	0.69	46.7	73.3
Kentucky	75 per cent. Pond Creek	20.0	75.0	0.55	0.49	33.2	66.8
Kentucky	75 per cent. Pond Creek	22.0	76.0	0.64	0.67	20.4	79.6
Kentucky	50 per cent. Elkhorn	20.0	80.0	0.69	0.68	21.2	78.8
Kentucky	75 per cent. Pond Creek	20.0	75.0	0.52	0.48	30.9	69.1

H_2S from the coke continues, however, through the later stages of carbonization.

Elimination of Sulphur in Coking. Table 14 (quoted from Sperr [16]) shows actual results, in coking operations, of analysis of the sulphur content of coke and coal. It appears that coal loses a large part of its sulphur (25-40 per cent.) in coking, but the percentage sulphur content in the resulting coke may be only slightly, if at all, lower than in the coal. There is a wide and irregular variation among coals in this behavior, making an advance estimate of behavior impossible.

It has been noted in actual practice that in bee-hive coking the elimination of sulphur is less than in by-product coking; in other words, a greater proportion of the sulphur remains in the coke in the bee-hive practice. Powell's demonstration (see page 102) of a secondary reaction of the hot coke oven gases containing hydrogen upon the sulphur compounds of the coke, may offer explanation of this fact. The gases, in the by-product oven, traverse the coke more thoroughly than in the bee-hive.

The Sulphur in Coke. The behavior of the sulphur in coke in the course of the reactions of the iron blast furnace and cupola is held generally by metallurgists to be of importance, as affecting the sulphur content of the iron.

A. R. Powell [17] and John H. Thompson [18] have made investigations on a laboratory scale which indicate that contamination of the iron with sulphur comes almost entirely from the ferrous sulphide form of sulphur in the coke, and is produced chiefly by actual contact of coke and iron in the spongy-iron zone of the furnace. Sulphur in the form of a carbon-sulphur "solid solution" (usually more than half of the total present) apparently does not pass into the iron. Steaming of the coke so as to reduce the sulphide sulphur on the surfaces of the pieces is suggested as a means of reducing contamination of the iron.

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[16] F. W. Sperr, Jr., *Jour. of the Franklin Inst.*, 1918, pp. 162-3.

[17] *Trans. Amer. Inst. Min. & Met. Eng.*, 1923.

[18] Bureau of Mines, Report of Investigations Nos. 2518 and 2469, 1923.

The form of occurrence of sulphur in coke has been proven by Powell,[19] through a physico-chemical study of dissociation pressures, to be (a) solid solution of sulphur in carbon and (b) ferrous sulphide.

Desulphurization of coke by roasting in air at 500° C. has been investigated by Powell [20] and some reduction of sulphide sulphur obtained. The rate, however, was found hardly practicable for industrial application.

Desulphurization by steam is in progress of investigation by the Bureau of Mines and preliminary reports (noted in *Coal Age,* May 3, 1923) are favorable to a probable reduction of 25-50 per cent. in sulphide sulphur.

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[19] *Jour. Amer. Chem. Soc.,* 45, 1-15 (1923).
[20] *Coal Age,* 23, 899-901 (1923).

Chapter 7.

Primitive Methods of Coal Carbonization—The Bee-Hive Oven.

General. Following the early coke-making in mounds, which resembled charcoal "burning," there was developed the bee-hive oven. The latter process is still used, to an important extent, notably in England and America, in spite of the fact that it burns all of the gas and by-products from the coal, and gives a coke-yield averaging 8-10 per cent. below that of the by-product oven.

The reasons for the retention in some measure of this method of coking are economic, incongruous as the word may appear in this connection, as the system has in its favor the elements of simplicity and low plant cost. These considerations have been set forth in detail in Chapter 3, pages 56-8.

Growth of Coke Production in the United States. Since 1918 there has been a rapid decrease of the percentage of bee-hive coke made in the United States. In 1919 by-product coke manufacture for the first time in this country exceeded that of bee-hive, and in 1922 the percentage of the total coke held by the bee-hive had fallen to 22. Figure 10 and Table 62 (in Appendix) show these relations.

The Bee-Hive Process. The characteristic feature of bee-hive coking is the production of the necessary heat by combustion *within* the oven. Coal lies in a horizontal layer on the hot floor of the oven and is coked downward by the heat of the burning gases in the dome. Air, accordingly, must be admitted to support combustion, the door in the side of the oven being left partly open for that purpose, and the charging hole in the top also being open, to allow escape of the products of combustion.

The control of air supply, in such manner as to hold the burning of the gases above the charge and cause a minimum of burning of the coke itself, is an element of large importance in bee-hive oven operation. The amount of air requires reduction as the coking proceeds and as the volatile matter remaining in the coke decreases. During the latter stages of the coking period, burning of the coke takes place unless the air is very carefully controlled.

The charge of coal is from 5 to 6 tons and is coked either 48 or 72 hours according to the grade of coke desired.[1]

The coke, when completed, is quenched or "watered" while in place in the oven, and is then "drawn" either by hand or by special machine. The quenching within the oven gives the coke a silvery luster and assists in preserving the long heavy pieces, both these qualities being characteristic of bee-hive coke and at one time held to be marks of superiority.

The Bee-Hive Oven. Figure 16 shows the common form of bee-hive oven. It is frequently built in rows or banks, either single, or double, back-to-back. Larry tracks run along the top of the banks of ovens for dropping the coal through the charging hole, or "trunnel head."

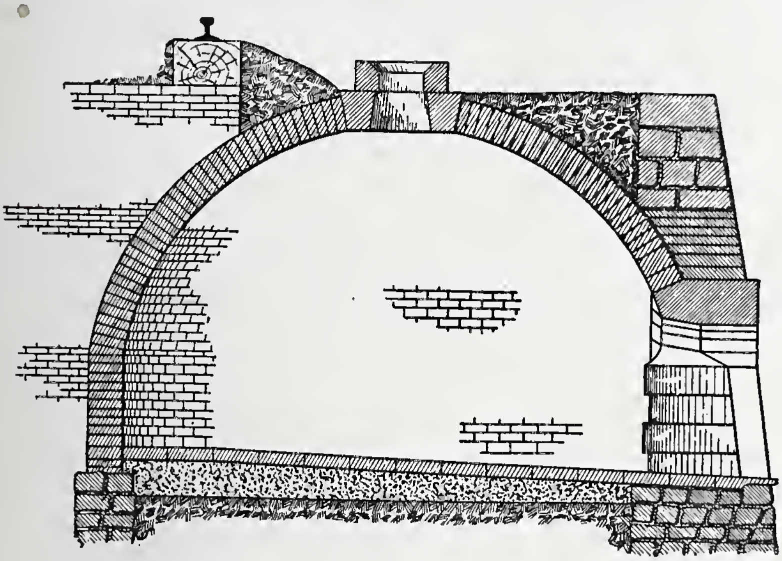

Fig. 16.—Typical Bee-hive Coke Oven.

The "longitudinal oven," or "rectangular oven," illustrated in Figure 17, is a modification of the bee-hive and is similarly operated, except that it has two doors opposite each other accommodating a pusher ram which discharges the coke.

Comparison of Bee-hive and By-product Ovens, in size and shape and in form of the coke: In Figure 18 (from Technical Paper 50, Bureau of Mines, by A. W. Belden, page 27) may be seen the relative size and form of the two types of oven, and the manner in which the coke shapes itself by the two systems of heating. In the by-product oven, the heating is from two sides toward the center, which causes thus formation of a cleavage plane in the center of the charge, and produces short and blocky pieces of coke as compared to the long columnar structure of the bee-hive coke.

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[1] For detail of bee-hive oven operation see: A. W. Belden, "Metallurgical Coke," Bureau of Mines Techn. Paper 50 (1913); Geo. H. Harris, "Bee-hive Oven Operation," *Coal Age*, 15, 44 (1919).

Recovery of Waste Heat in Bee-Hive Coking. In many of the more modern installation of bee-hive ovens waste heat recovery, by steam raising, is successfully practiced, and effects considerable economies. In fact, it may be said that nearly all of the heat of the burned gases (over and above what is reasonably to be charged to the coking of the coal) is recovered in steam. There still remains a loss, however, of about an equal amount, equivalent to the heat of the burning of the tar and one-tenth of the coke.

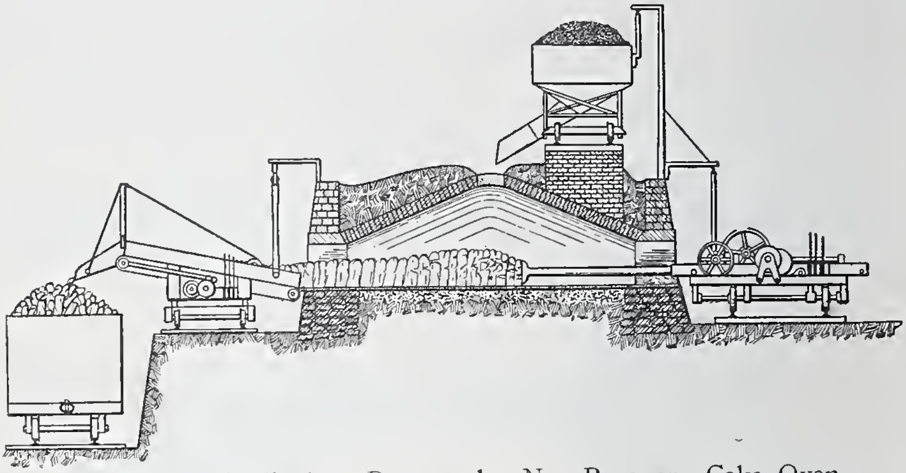

FIG. 17.—Longitudinal or Rectangular Non-Recovery Coke Oven.

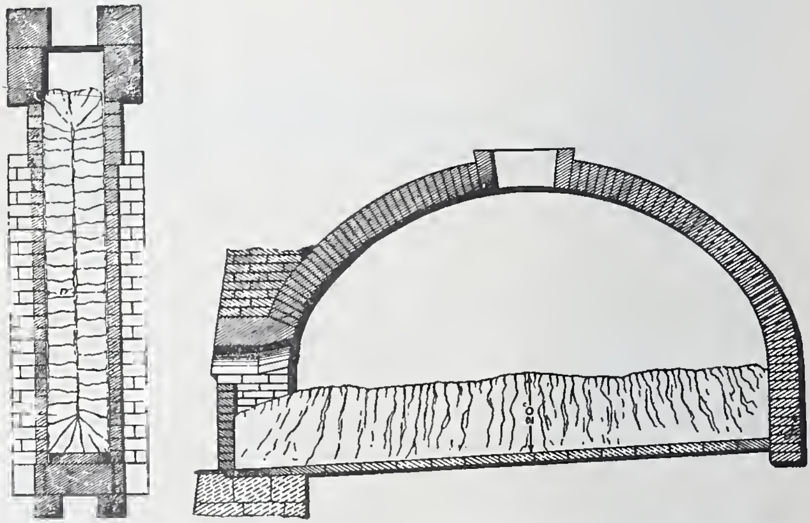

FIG. 18.—Comparison of Bee-hive and By-Product Coke Ovens and their Charges. (After A. W. Belden and the U. S. Bureau of Mines.)

Good installations have recovered in steam 15 to 20 horse-power per oven per hour,[2] or 1 HP from 15 pounds coal coked per hour.[3] This is equivalent roughly to a recovery of 1,800 B.t.u. per pound of coal coked if the steam-raising performance be compared to that of a direct coal fired boiler using 2 pounds per HP-hour. The heat distribution, thus, in improved methods of bee-hive coking, may be expressed approximately as follows:

TABLE 15.

Original heating value, 1 pound coal		13,500 B.t.u.
Remaining in 0.63 pound coke		8,060
Burned in oven to effect coking:		
0.07 pounds coke	900	
0.06 " tars and oils	1,000	
5.5 cubic feet gas	3,200	
Total used for coking (of which 1,800 is recovered)		5,100
Miscellaneous losses		340
Total		13,500

The installation for waste heat recovery consists (Figure 19) ordinarily of a tunnel or flue, running between the two banks of ovens, and a connecting flue passing thereto from the "trunnel-head" of each oven or through a lateral opening in the trunnel-head. The waste gases, consisting of the products of combustion, with little or no unburned gases, are at a temperature of 2,100°-2,500° F. when leaving the ovens and may reach the boilers at 2,000°.

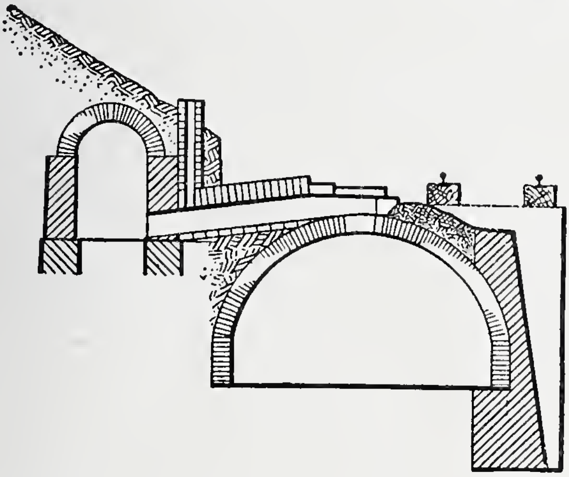

FIG. 19.—Bee-hive Oven with Waste Gas Flue.

[2] A. W. Belden, Techn. Paper 50, Bureau of Mines, p. 20.
[3] Arthur D. Pratt, *Chem. & Met. Eng.*, 1917, 27.

The Jones and Laughlin Steel Co., at Aliquippa, Pa. (near Pittsburgh), has a large waste heat boiler installation on two banks of bee-hive ovens, the recoveries from which are reported to be an entirely satisfactory return on the investment. The H. C. Frick Coke Co. operates waste-heat recovery at a number of its plants.[4]

The wastes of the bee-hive coking industry are not to be counted entirely in by-products burned or coke yields reduced. There is a loss, less tangible, but still of large importance, resting in the undue consumption of the best grades of gas and coking coals, unmixed with coal of inferior rank and consumed at efficiencies occasioning extravagance. With the retort ovens, 15-18 per cent. less coal is required, and the highest grades may be conserved by admixture with others of lower rank and more plentiful in supply.

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[4] The Star Junction (Pa.) plant of this company is described by C. R. Weihe, in *Coal Age*, Sept. 2, 1920. Arthur D. Pratt, *Chem. & Met. Eng.*, 1917, 27, also discusses fully the principles of waste-heat recovery from bee-hive ovens, and gives average returns.

Chapter 8.

By-Product Coking—The Working of the Plant.

General. In a previous chapter (Chapter 3), coking in by-product recovery ovens has been compared in principle with other processes of carbonizing coal. It remains here to trace briefly the essential general features of the equipment and the process, common to all types of oven, and in another chapter then to describe and illustrate the various individual types.

The by-product coke oven is a long and narrow chamber, built in groups or batteries, for carbonizing coal in relatively large bulk. It is heated ordinarily by combustion of the gas evolved from its own charge of coal, this gas being first stripped of certain valuable by-products. Other gases may, however, be used.

A strong and carefully built structure of refractory brick, the oven battery comprises (1) the oven chamber proper, usually rectangular, horizontal and narrow; (2) the heating flues, several in number flanking the oven chamber on two sides, and (3) the various accessory structures integral therewith to lend support and foundation, heat insulation, and facilities for waste heat utilization by regeneration. A block or battery is usually of 30 to 90 ovens.

There is considerable variation in size of oven among the different types and installations, but an average modern oven chamber may be described roughly as 38 to 40 feet long by 10 feet high, tapering in width from 17 or 18 inches at one end to 15 or 16 inches at the other. Until comparatively recent times, the average American oven was from 2 to 4 inches wider and somewhat less in height and length. The cubical content is 530 cubic feet, and when charged, as ordinarily, to within 12 inches or 14 inches of the top, the average oven holds 480 cubic feet of coal or about 12 tons. Some of the larger American ovens receive a charge as great as 16 tons. 2 ✓

The by-product coke oven is one of the most elaborate and costly of masonry structures, being erected with closest attention to engineering detail, to withstand the severe strains incident to its use. The longitudinal expansion in a battery of ovens during the "heating up" process frequently amounts to as much as four feet, yet every wall must remain straight and every flue tight. The strain of pushing coke from an oven—a long narrow body moved by pressure at one end,

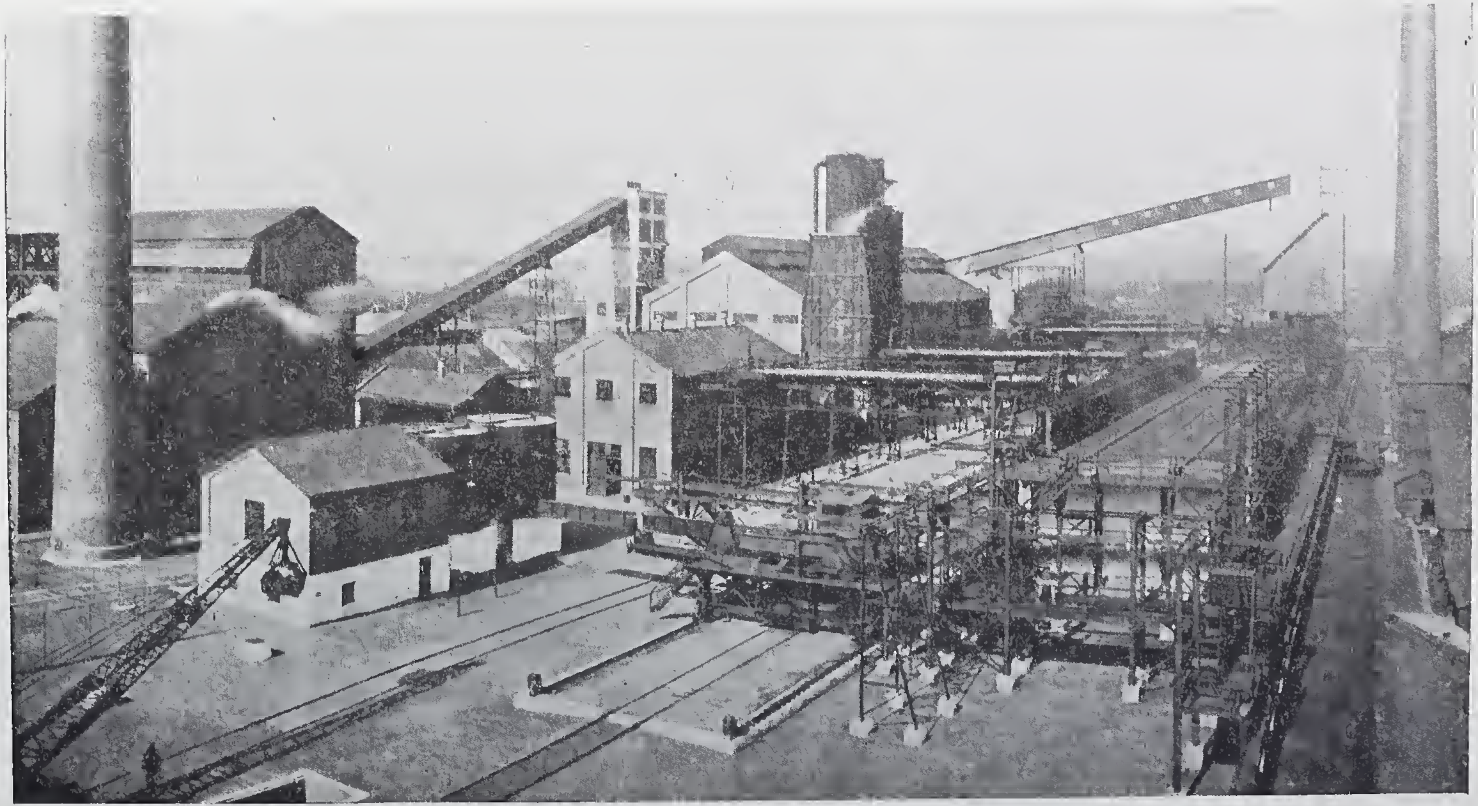

Fig. 20.—General View of Typical By-Product Coke Works, showing Ovens and By-Product Recovery Buildings.

and creating considerable friction—is indicated by the fact that power measurements show the thrust on the coke to amount oftentimes to 25-30 tons.

The by-product coke oven is designed primarily to produce coke. On this account it carbonizes relatively a large bulk of coal as compared to the gas retorts designed primarily for gas production. The coke oven produces nevertheless a good grade of coal gas, suitable for town supply, as has been noted in Chapter 3, page 61. By reason of the bulk of the charge, the slower rate of carbonization and the longer period, during which the carbonized coal remains at a high temperature, the coke oven can produce better and harder coke for the special uses of metallurgy, than can the gas retort. It is this fact commonly that justifies and repays its high first cost.

Since coke constitutes 70-80 per cent. by weight, of the products of coal carbonization and from 50 to 75 per cent. of their value, a variation in quality of the coke, affecting its economic value, has large influence on the commercial success of the plant. A full and sustained coke market at favorable prices or an assured consumption of this product within the plant, as for water gas, is essential to the success of a by-product coke oven plant, even though such plant may exist primarily to supply gas.

Summary of By-Product Coking Process.

The by-product coke oven is intermittent in operation. Into the oven at a bright red heat (say about 2,000° F. at the walls), the charge of finely crushed coal is dropped through charging holes in the top, usually four in number. The first rush of gas, steam and air thus caused is allowed to escape through an outlet valve in the uptake pipe which rises from top of the oven near one end, this same valve operating to close communication temporarily with the gas main. After the charging holes have been covered and sealed, and the surface of the coal levelled in the oven, the escape valve from the uptake pipe is closed, thereby simultaneously opening the passage from uptake pipe into the primary gas main or "collecting main." The oven then, in common with its neighbors in the battery, is in communication with the gas-scrubbing and collecting system. In this system is a mechanical exhauster pulling just hard enough to maintain even pressure or very slight variation therefrom in the interior of the ovens. An automatic "governor" in the suction mains controls this pressure.

The processes and apparatus for gas scrubbing and by-product recovery are described in another chapter (Chapter 11, pages 278-311). The coal gas from the oven, freed in the coolers, scrubbers, etc., of its content of tar, water, ammonia and various light oils, is collected and in part returned to the heating flues surrounding the oven, for combustion there with preheated air. In well-designed modern, regenerative ovens, that is, ovens utilizing the waste heat of the flue gases for preheating the air for combustion, not over 40 per cent. of the total "oven gas" is required thus for fuel.

The charge remains in the oven until it is completely coked from wall to center, or, in other words, until the evolution of volatile matter has practically ceased, when the gas outlet valve is closed. After remaining a short time "dampered," the oven doors at either end are removed by electrically operated machine or by hydraulic lift, and the hot coke discharged by the pusher ram. The latter is operated by an electric motor on the pusher machine, which travels from oven to oven on a track in front of the battery. The hot coke falls into a quenching car travelling along the battery on the opposite side, and is hauled therein by electric or steam locomotive to the quenching station. Further details of charging, discharging and quenching operations may be found in later paragraphs.

Coal Preparation and Quality.

The coal handling plant and the crushing, mixing and stocking system at a coke plant is an exceedingly important part of the establishment. Thorough and uniform mixing when two or more coals are used, regularity in proportions, and regularity in maintaining full charges to the ovens, are factors essential to efficient operation.

Storage. The risk of damage to the ovens by shut-downs, and of serious loss also to the consumers of coke or gas, makes it necessary to guard against any possible interruption of coal supply by provision of an adequate reserve storage, usually at least one month's supply. This is placed, as a rule, in open piles. Plants located on waterside, where coal deliveries by steamer or barge are cheaper and more satisfactory than by rail, often store several months' supply, in order to tide them over the season of closed navigation. As much as 400,000 tons has been stored at one time by certain coke plants on the Great Lakes.

The effect of storage on the quality of the coal is likely to be injurious if continued longer than three or four months. This is due, however, not to mere aging or exposure of the coal, but to some measure of autogenic heating therein. It varies also with conditions and with the kind of coal.

It is doubtful whether the high grade coking coals, piled so as to remain entirely free of spontaneous heating, are materially affected as to coking quality and by-product yields. Definite records of experience tending to answer this question are lacking, and the difference of opinion frequently expressed arises perhaps from lack of certainty as to the occurrence of heating in the piles. There is no doubt that even moderate heating has a disturbing influence on the coking and by-product giving qualities of coal,[1] and such heating (without actual fire or incandescence) is very prevalent in large piles. In all probability many cases of observed detriment to coking quality have been caused by this factor.

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[1] See report of tests on this, Wm. Seymour, *Blast Furnace & Steel Plant*, 1920, 435; also review of subject by Stoek & Freeman, *Iron Trade Rev.* (1922), 1207 and 1272.

Spontaneous heating may be minimized in coal piles and occurrence of trouble made rare, by observing simple precautions and giving reasonable care and observation to the piles during storage. The manner of piling the coal, the degree of penetration of air into the piles, the presence of dust due to breakage in handling, the placing of the piles contiguous to heating pipes, flues or walls, and on loose or porous bottoms, all these are factors of greater importance in spontaneous heating than are the composition of the coal and the chemical behavior of its components and impurities. Heating of the coal stocks results from the retained heat of slow oxidation *of the coal substance,* the carbonaceous material, and is controlled by the supply of oxygen and the cooling of the material by air currents. When the air can penetrate the pile at a rate fast enough to oxidize fine coal in the interior and develop heat more rapidly than it is carried away by the air currents, a continuous rise of temperature results.

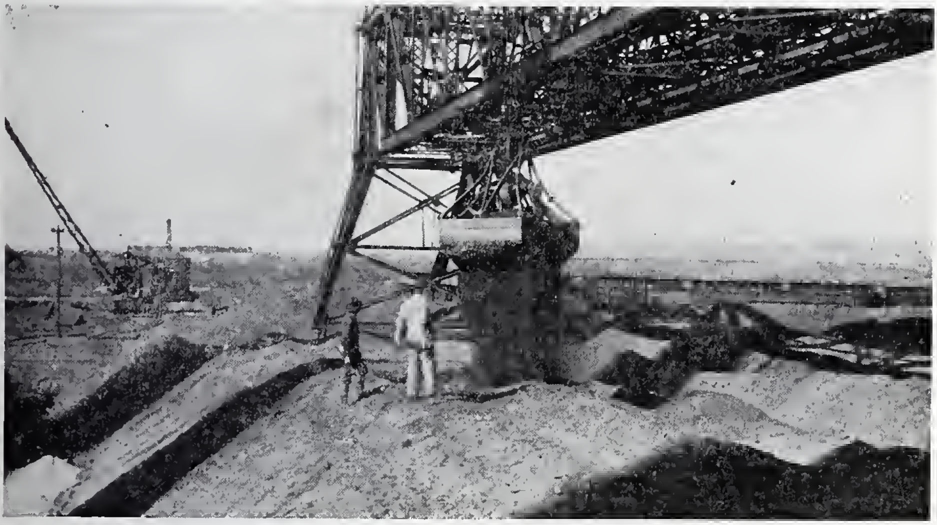

Fig. 21.—Storing Coal by Travelling Bridge and Clam-shell Bucket (showing correct method of piling evenly).

Piling of coal evenly in layers rather than in pyramids, from which the lumps roll down and form air channels at the bottom, constitutes, therefore, one of the most effectual safeguards (see Figure 21). Screening before placing in storage is also effectual if practicable. These and other precautions are noted and explained in Technical Papers of the Bureau of Mines [2] and in bulletins of the University of

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[2] H. C. Porter and F. K. Ovitz, "Deterioration and Spontaneous Heating of Coal in Storage," Techn. Paper 16, Bureau of Mines, 1912; H. H. Stoek, "Safe Storage of Coal," Techn. Paper 235, Bureau of Mines, 1920.

Illinois Engineering Experiment Station[3] to which the reader is referred for more detail on this subject.

The coal piles at a coke plant should be watched closely for temperature rise, by systematic and regular inspection, using iron rods driven into the pile at points where heating is indicated by odor or by slight steaming. The rods, on being withdrawn, show to the touch the approximate degree of heating. Any sections which indicate a temperature higher than 125°-130° F. (such as can be borne easily by the hand), should be dug out and consumed, or rehandled by spreading over the surface of the pile. In this way serious and extended heating with its marked deteriorating effect on coking quality and the loss of perhaps thousands of dollars in by-products may be prevented.

"Rotation" of the coal stock, or removal of the oldest coal first, is practiced at many plants. It is, however, well established by recorded experience[4] that in the majority of cases a pile which has stood three months without serious heating is safe to remain longer. It would, therefore, appear to be good practice to watch most closely the portions which have been from three to twelve weeks in stock, and to consume first those showing the greatest degree of heating.

Concrete pits for coal storage have in the last few years been installed at a number of plants, instances being those of the Illinois Steel Co., at Joliet, and of the Duquesne Light Co., on Brunot's Island, Pittsburgh, Pa., of capacities of 50,000 to 100,000 tons respectively, (below the basin top). Access of air to the lower portions of the pile may be largely prevented in these pits even without recourse to underwater storage.

Coal Washing. Detailed description of coal washing processes and equipment is hardly within the scope of this Monograph. The subject is a large one, and not of direct bearing on Coal Carbonization. It is referred to here, therefore, merely in outline.[5]

Washed coals, to be sure, are frequently used for coke making. In many cases it may be that a certain coal which is most available to the works, and cheapest, carries too high a content of ash or sulphur to make coke suitable to the purpose in hand, and washing may reduce these constituents to a practical percentage at costs less than the freight differential on more distant coal. The coking quality of a coal, however, is not concerned in an important degree with its ash or sulphur content, and the reduction of these incidental impurities by cleaning is by no means a normal adjunct to coking operations.

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[3] S. W. Parr and F. W. Kressman, "The Spontaneous Combustion of Coal," Bulletin 46, Univ. of Illinois, 1910; S. W. Parr, "Effect of Storage on the Properties of Coal," Bulletin 97, Univ. of Illinois, 1917; H. H. Stoek, C. W. Hippard and W. D. Langtry, "Coal Storage Practice," Bulletin 116, Univ. of Illinois, 1920.

[4] "Bituminous Coal Storage Practice," by H. H. Stoek and others, Univ. of Illinois Engineering Experiment Station Bulletin 116, pp. 46-47.

[5] The following references will furnish detailed information on coal washing: Ernst Prochaska, "Coal Washing," McGraw-Hill Book Co., Inc., New York, 1921; J. R. Campbell, *Bull. Amer. Inst. Mining Eng.*, 153, 1779 (1919); "Coal Washing in Illinois," F. C. Lincoln, Bull. 69, Univ. of Ill. Eng. Expt. Sta., 1913; G. R. Delamater, *Coal Age*, **22**, 664-666 (1922).

On account of the deleterious effect of sulphur on certain physical qualities of iron and steel, there is customarily demanded for iron blast furnace use a coke of less than 1.2 per cent. sulphur, and for foundry use one of less than 1.0 per cent. sulphur. For these purposes eighty per cent. of the coke output of America is now used. For ash, there is a somewhat less definite limitation, depending in a measure on individual preference, but commonly placed at a maximum of 10 per cent. ash in the coke, more than which is likely to exert objectionable influence in furnace operation.

The sulphur of coal, during the coking process is eliminated[6] to the extent of 30-40 per cent. (varying with the kind of coal), but ash on the other hand remains in the coke almost in its entirety. Good coals, therefore, for the making of metallurgical coke are in best practice limited to maxima of 1.0-1.1 per cent. sulphur and 7.0 per cent. ash.

A number of by-product coke plants find it impracticable, without prohibitive cost, to secure coals of this quality. These plants (if conditions demand it) resort to *coal washing*. At the present time (1923) probably not over 10 per cent. of the coke made in America is from washed coal, but this percentage is likely to increase on account of the growing difficulty in securing low sulphur coking coals.[7]

The separation of the impurities from coal by washing depends upon the difference in specific gravity between the pieces of purer coal on the one hand and the pieces of foreign matter or of impure coal on the other hand which contain slate, pyrites or other mineral matter. Sulphur occurs in coal not only as pyrite but also in the form of organic compounds well disseminated throughout the coal substance; and further, in small amount as sulphates of lime, iron or magnesia. These forms of sulphur, as well as the finely divided and diffused mineral matter of the old plant tissue, are not readily removed by washing.

By no means all of the coals of high sulphur or ash content are susceptible to cleaning in adequate measure and economically by washing.[8]

While the various coal washing processes and types of apparatus cannot be described here in detail, it may be stated, in general, as to the process, that the coal is crushed, mixed with water, and agitated in such manner as to stratify the heavier and lighter parts, carrying off the latter mechanically with the flow of water. There are used in coal washing, "jigs," which maintain a pulsation in the fluid mixture by means of a plunger, and "concentrating tables," inclined and agitated, similar to those of ore concentration practice, over which the fine coal and water flow. Tables are used mostly on the finer sizes separated from the crushed coal by screening, or by "classifiers." Separation of the coal into sizes before washing is found in some cases beneficial, particularly often to by-pass the fines and treat them separately. The degree of crushing necessary before washing depends greatly on the kind of coal and the nature of its impurities, but a reduction to 1¼ inch size and under is common. The amount of water used in washing is generally 1½ to 3 times the weight of the coal.

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[6] See Chap. 6 on the behavior of sulphur compounds during coal carbonization, and the investigations of Powell and others therein reviewed. Also *Gas Age*, 1921, pp. 83-85.

[7] In Bulletin No. 153 (Sept. 1919), American Institute of Mining and Metallurgical Engineers, p. 1779, J. R. Campbell, Chief Chemist of the H. C. Frick Coke Co., says: "Coal washing is rapidly coming into its own, due to the depletion of low-sulphur coals for coking purposes, and before many years we predict as careful attention being given to the design and construction of coal washeries as is now being given to by-product plants and other allied industries."

[8] An important study of the occurrence of sulphur in different parts of the coal bed and the physical forms thereof has been made by Frazer and Yancey, Bulletin 125, Univ. of Illinois Engineering Expt. Sta.

As to efficiency of coal washing, the condition of the impurities greatly affects the results, but in average practice it may be said that the percentage of sulphur in the coal is reduced by 30-40 per cent., and of ash by 50 per cent. Expressed in another way, washing removes in the tailings at least 50 to 55 per cent. of the total ash and sulphur and not much over 1 per cent. of the good coal. The tailings amount to 10-15 per cent. of the original coal. The effluent water from the washery carries finely divided coal amounting to between 2 and 5 per cent. of the raw coal, and in good practice this is largely recovered in so-called "thickeners" or settling tanks, from which the sludge may be removed and added to the washed coal either before or after drying.

The moisture in washed coal (bituminous) is likely to vary from 5 to 15 per cent., depending on whether mechanical dryers are used, and how successful they may be upon the coal in question. It is extremely difficult to expel mechanically the water held by fine coal, and for this reason the question arises in many cases whether the fines should not be screened from the raw crushed coal before washing. In washed coal as charged to the ovens, the content of moisture, over and above the initial in the coal as mined, should not exceed 3 or 5 per cent. (that is, a total moisture in the Eastern coking coals of 6 or 7 per cent., and in the Illinois type of 10 or 11 per cent.). A greater amount causes excessive spalling of and injury to the oven linings.

Dry "Concentration" or purification of coal for coking purposes has a number of points in its favor, and accordingly the commercial application of such methods is increasing. Chief among these points are (1) the avoidance of the troublesome and expensive process of drying the washed coal, particularly the fines, and (2) avoidance of excessive cooling of the oven walls by moisture, and saving of the heat used in evaporation of the moisture in the oven. The processes thus far proposed, however, require fine pulverization of the coal, and have not fully demonstrated their economic success in point of costs and yields. The dust problem, with some coals, is a serious one. The processes of W. W. Bonson[9] and of Sutton, Steele & Steele[10] depend upon agitation of the finely pulverized and (preferably) sized coal upon inclined tables by a current of air.

Dry-cleaning plants, using the Sutton, Steele & Steele apparatus, under the name of 'American Pneumatic Separator,' have recently been put into successful commercial operation, one at McComas, W. Va. (for American Coal Co.), and another at Wyco, W. Va. (for the Wyoming Coal Co.). The latter installation is said to be of a capacity of 150 tons per hour.[11]

A paper by Edw. O'Toole read before the American Iron & Steel Institute in 1921 (Iron & Coal Trades Review, 102 (1921), 819) described the working of one of these dry concentrators, handling 10 tons per hour.

The Chance "Flotation Process," applicable both to anthracite and bituminous coal[12] uses for washing, a liquid medium, in which the requisite specific gravity is maintained by suspension of fine sea sand in water. The purer parts of the coal float off in a current of water and adhering sand is removed by further washing on a screen.

The "Trent" Process[13] of concentration or purification of coal consists in a treatment of the finely pulverized material with water and oil, not after the manner of the well-known frothing or flotation processes applied to ores, but with a selective "wetting" of the coal particles by oil, forming an "amalgam," pasty in character, which settles out of the aqueous suspension of the mineral impurities. This "amalgam" or "concentrated" coal may be heated or distilled to remove oil and water, or for some purposes may be used direct. This process has received much favorable attention, but is at present writing still in the experimental stage.

Recent experimenters[14] both in America and England, notably Minerals Separation, Ltd., have applied froth-flotation processes successfully to coal. By agitating 10-mesh coal with 4 to 6 times its weight of water and 1 pound per ton of an oily reagent, the Minerals Separation process has reduced the ash content from 10.14 to 3.25 per cent., the purified coal, amounting to 87.2 per cent., floating off in the froth.

[9] Brit. Pat. No. 10,831 (1913).

[10] U. S. Patents 1,141,852, 1,215,880 and 1,315,881.

[11] "Dry-Cleaning of Coal," by Ray W. Arms, Engineer, Roberts & Schaefer Co., Chicago, Illinois, a paper presented to the American Institute of Mining and Metallurgical Engineers, February, 1924.

[12] H. M. Chance, "A New Source of High Grade Coal," *Iron Age,* **112**, 1713-14 (1923); D. C. Ashmead, "Plant Records and Layouts of the Chance Flotation Process," *Coal Age,* **21**, 735 (1922).

[13] *Coal Age* (Vol. 20, pp. 132-4 and 172-175), July 28, 1921, and Aug. 4, 1921, G. St. J. Perrot and S. P. Kinney.

[14] R. F. Bacon, in "American Fuels," Bacon and Hamor, McGraw-Hill Co., 1922, pp. 1170-2; U. S. Pat. 1,329,493, to R. F. Bacon; *Iron and Coal Trades Review,* **102**, 197 (1921); also Ernest Bury, in *Trans. Inst. Min. Eng.* (Brit.), **60**, 243 (1921). For American experiments, O. C. Ralston and A. P. Wichman, *Chem. & Met. Eng.,* **26**, 500 (1922); also Ralston in *Coal Age,* **22**, 911 (1922), and Bacon and Hamor, *Jour. Soc. Chemical Industry,* **38**, 161-168 (1919).

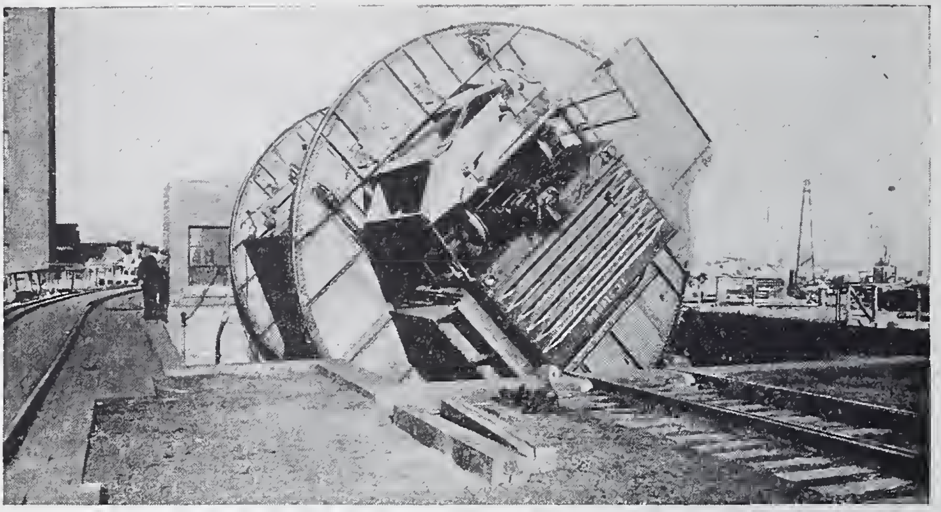

FIG. 22.—Car Dumping Machine.

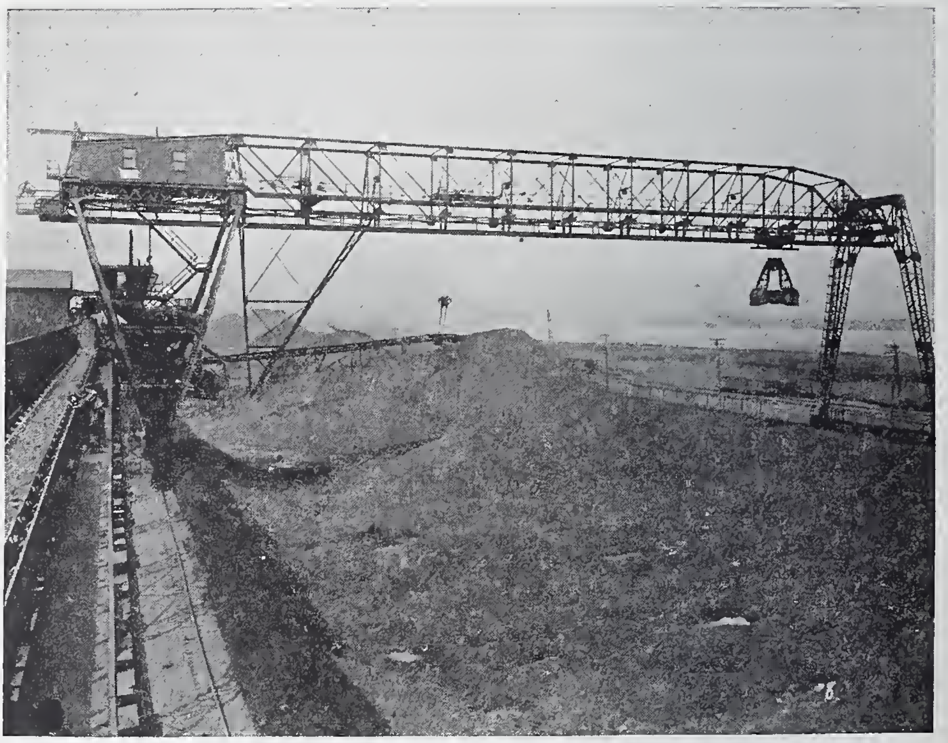

FIG. 23.—Coal Storage Pile, with Coal Handling Bridge and Belt Conveyors.

E. Bury and associates (*loc. cit.*) have worked on coal washery wastes of 40-75 per cent. ash, by such a process, at the Skinningrove Iron Works, England, and reduced the ash content to 9-14 per cent.

Coal Handling, Crushing, Grinding and Mixing.

Ordinarily, for by-product coking, run of mine coal, crushed so as to pass about a 1½-inch screen, or very commonly pulverized so that 65 to 90 per cent. will pass ⅛-inch mesh, is used for the oven charge. Especially, when two or more kinds of coal are mixed, is pulverization advisable, in order to secure uniform and high grade coke.

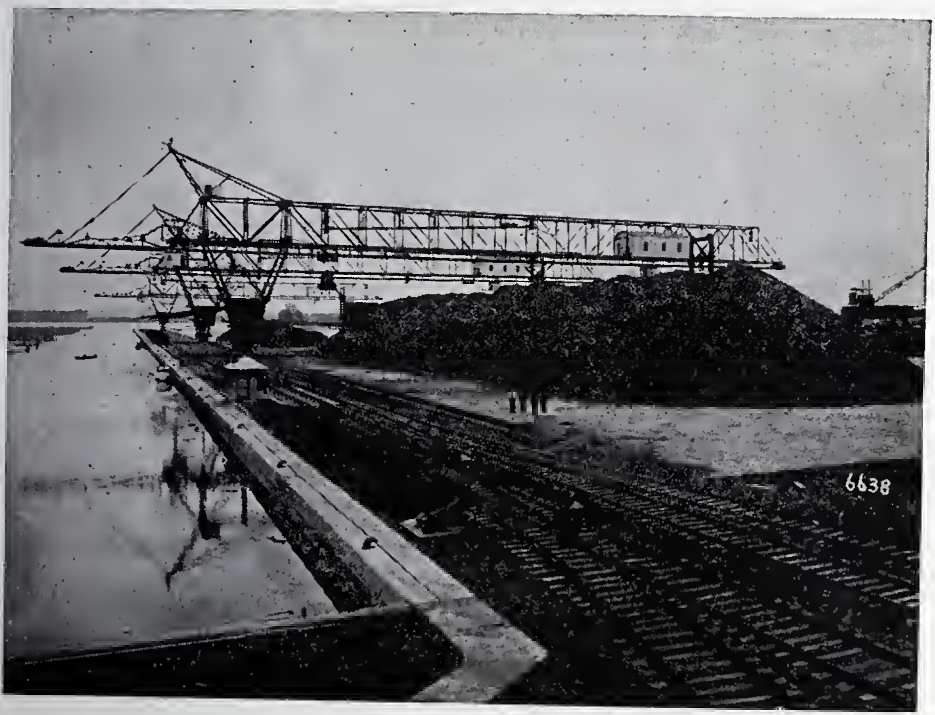

FIG. 24.—Coal Handling and Unloading Bridge at Docks.

Coal is received at the coke plant either in railroad cars which dump into a track hopper feeding onto a conveyor, or in barges docking near the plant from which cranes unload the coal in clam-shell buckets to railroad shifting cars or into elevated tipples to be fed therefrom onto belt conveyors. Railroad cars are in some plants lifted bodily by a car dumping device and emptied into bins which feed onto the conveyors. The conveyors carry the coal either to the stock pile or to the crusher building.

The illustrations (Figures 21-25) show examples of coal handling plants and stocking equipment.

For loading and reclaiming of large coal stocks, the overhead travelling bridge and gantry crane covering a rectangular space is most commonly used. For smaller installations the locomotive crane or drag-scraper systems are suitable. It is important that the coal storage system be large enough and flexible enough to provide easily for separate handling of the different kinds of coal and the necessary movement and transfers thereof. Confusion of the kinds and their proportions in the coal mixture charged to the ovens may easily lead to serious consequences in operating conditions and results.

The conveyors deliver the coal to the coal preparation building (Figure 26), in which it drops to the primary crushers or breakers. At the great majority of by-product coke plants these are of the type known as the "Bradford Breaker" (see Figures 27-28), which crushes by the impact of the falling lumps in a large rotating drum, and at the same time screens the coal and discards pieces of timber, slate, bony coal and the larger pieces of "tramp iron," accidentally carried in with the coal from the mines. Smaller pieces of tramp iron, spikes, bolts, etc., are often withdrawn from the coal on the conveyor belts by an overhanging magnet, or by magnetized pulleys, over which the belt passes. The drum of the breaker is provided at its periphery with round holes, usually of 1-inch to 1¾-inch diameter, through which the broken coal passes. Different kinds of coal vary in hardness and require corresponding variation in size of the perforations of the drum, the size of these holes also affecting the rate of output of the machine.

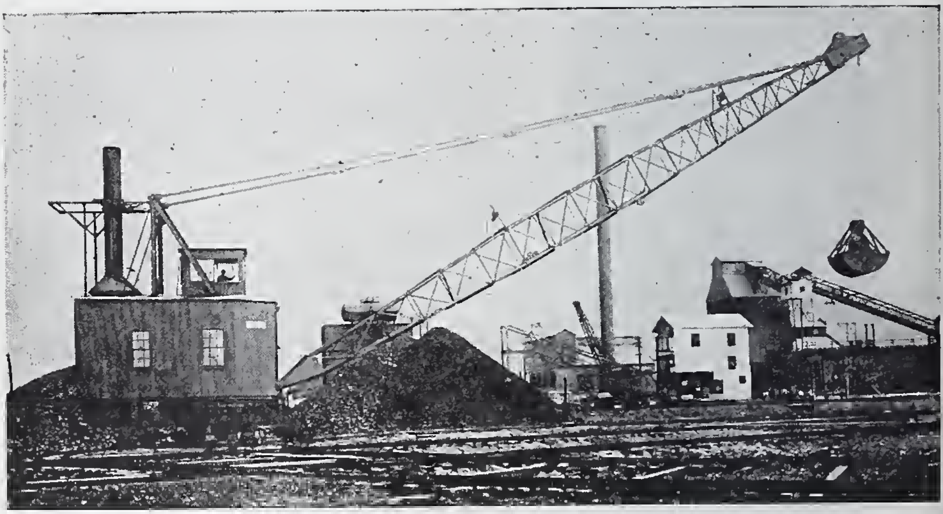

Fig. 25.—Locomotive Crane for Coal Handling.

Further comminution of the coal is secured if desired by crushers of either the "hammer-mill" or the double-roll type. The former is more common, and is illustrated in Figures 29-30. The heavy steel "swing-hammer" rotor (Figure 31) revolves at high speed and crushes

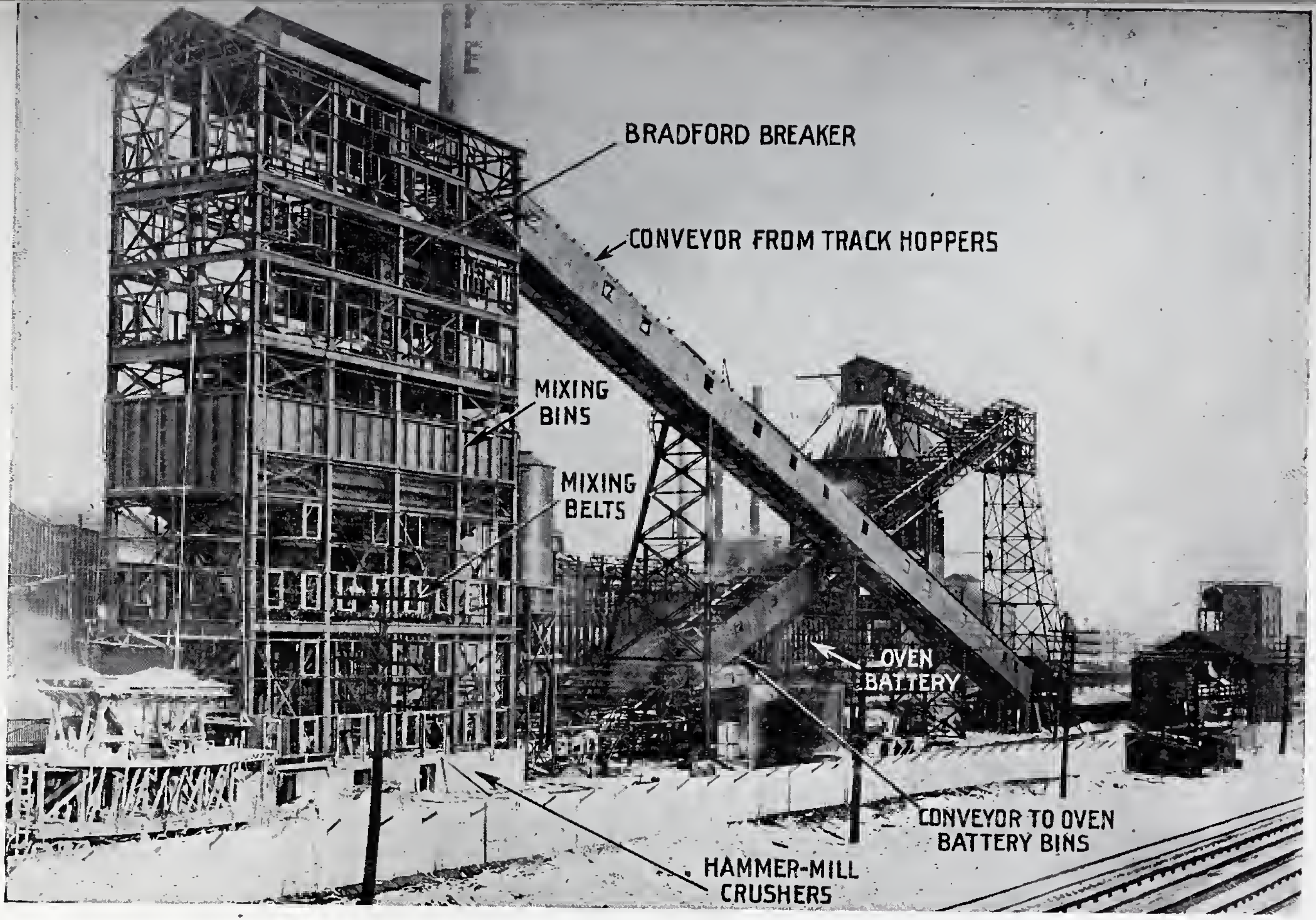

Fig. 26.—Coal Preparation Building, showing position of various crushers, mixers and conveyors.

by its hammering action. This type of machine with a rotor of 58-inch diameter at 720 R. P. M. is rated to deliver 150-200 tons of crushed coal per hour, 85 per cent. passing a ⅛-inch screen.

Most plants mix the coals after the primary crushing (1-inch size and under), the action of the pulverizing mill, which follows, promoting an intimate mixture.

Proportions in the mix are ordinarily controlled by delivering the coal into a hopper from two belts running at regulated speed on which the thickness of the coal layer is fixed by a knife or scraper. Belt scales, weighing the coal passing over, are also in use as a check. Another device for proportioning the mix consists of turn-tables at the bottoms of the different coal bins, turning at definite speeds and fitted with knives set to cut off the coal at definite rates, delivering it to the belt conveyors. Automatic shutoff devices are essential on these belts and turn-tables to shut down all of them whenever any one of them may be accidentally stopped.

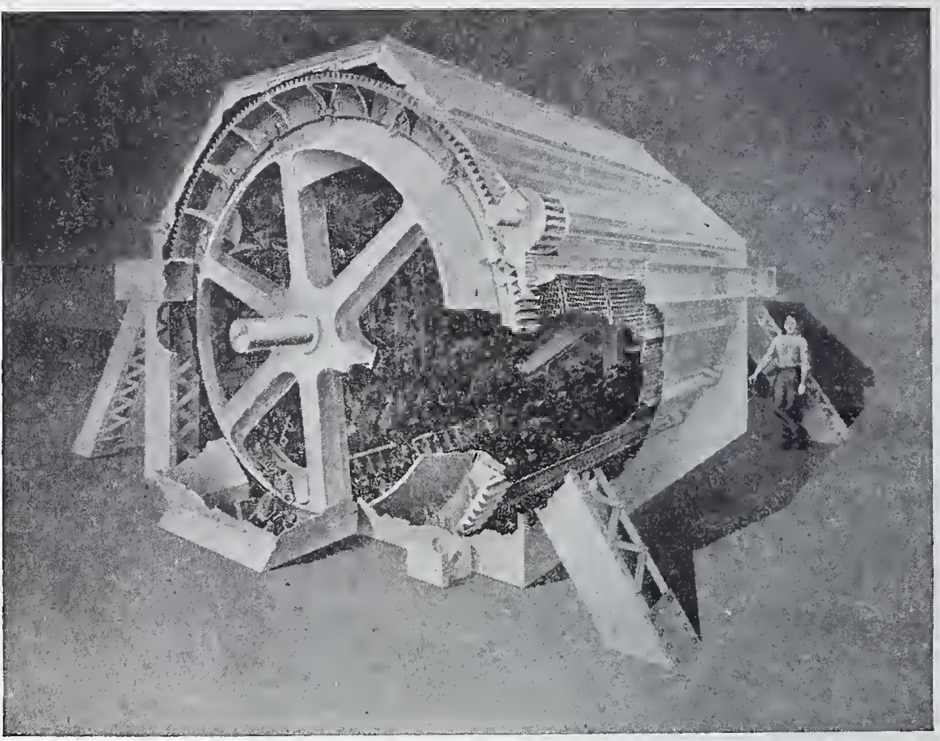

FIG. 27.—Bradford Breaker, phantom drawing.

The mixing of coals for by-product coking is largely an American development. It has been carefully worked out so that the effect of one kind of coal upon another as to quality of resulting coke and by-products is well known, and many coals can be used successfully which otherwise would not be practicable for coke making. Some of the

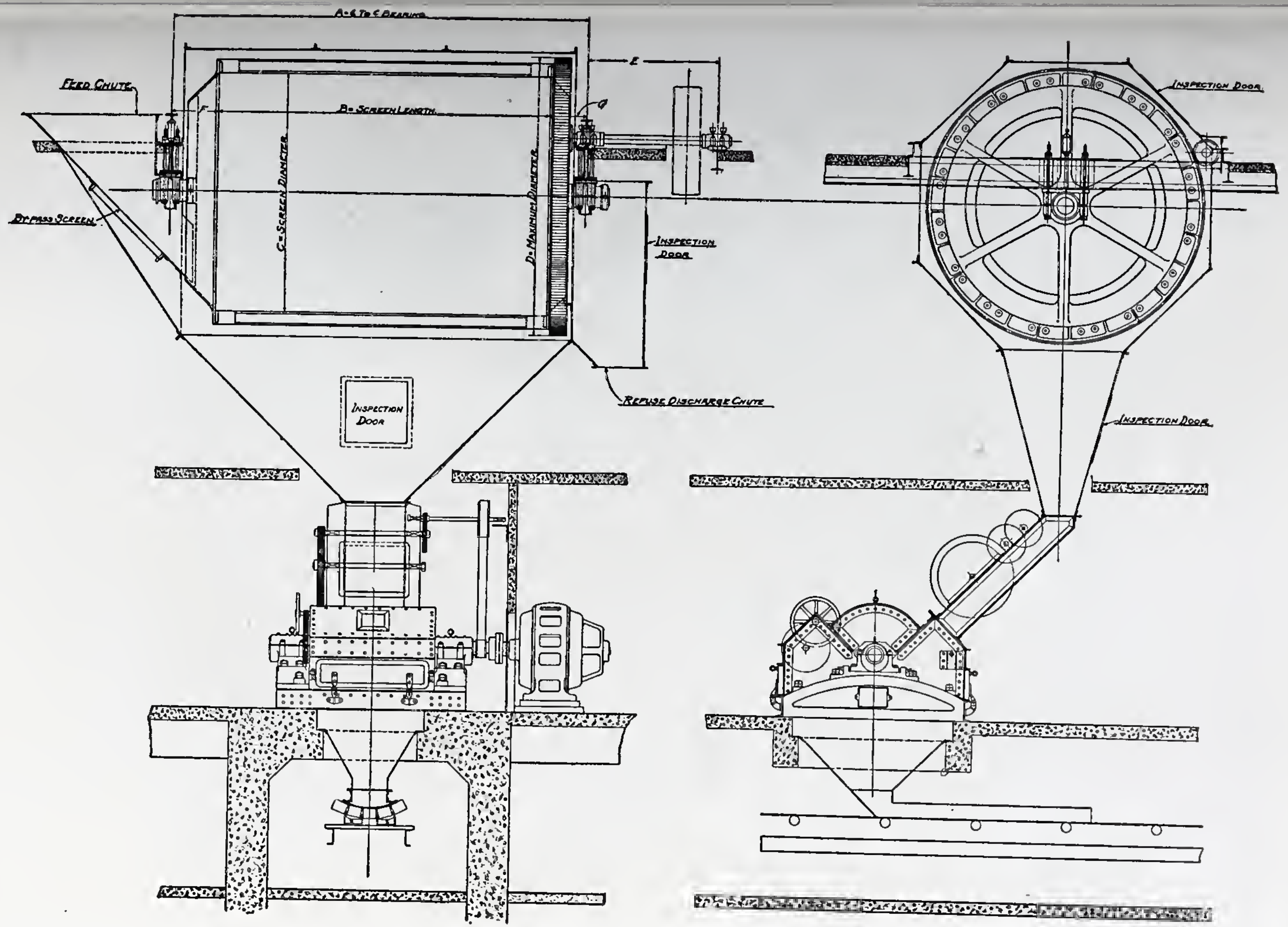

Fig. 28.—Arrangement of Bradford Breaker and Hammermill Crusher in Coal Preparation Building (drawing by Pennsylvania Crusher Co.).

largest and most modern plants, using but one kind of coal, avoid fine pulverization, and merely crush to 1-inch size or thereabouts. The resulting mixture of all sizes, from dust up to 1-inch, gives a greater weight per cubic foot, and therefore heavier charges in the oven, than does the very finely pulverized coal. Opinions differ as to the effect of the degree of fineness on by-product yields per ton, but prevailing experience appears to show an advantage in pulverization.

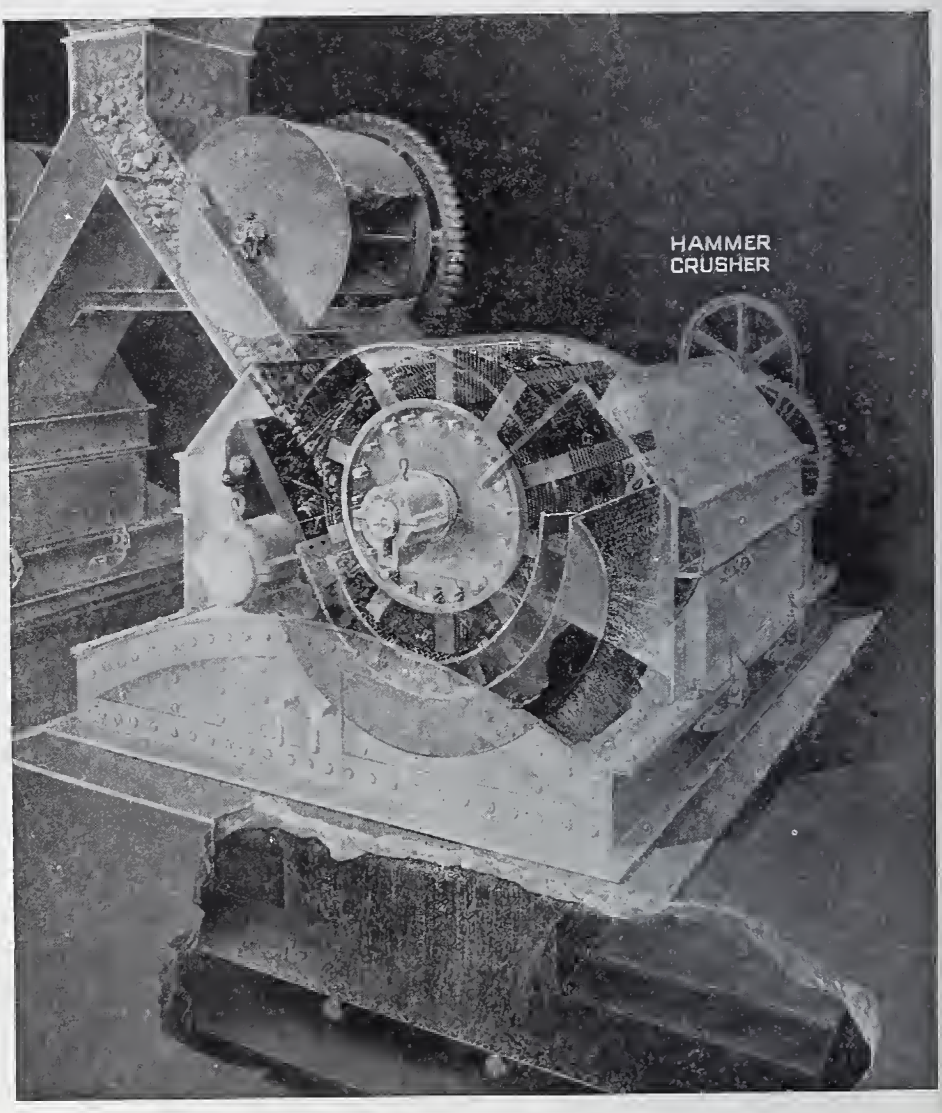

Fig. 29.—Hammermill Crusher, phantom drawing.

The physical character of the coal and of its impurities has much to do with the degree of betterment in coke quality by pulverization. When the coal is not pulverized, large pieces of slate may enter with

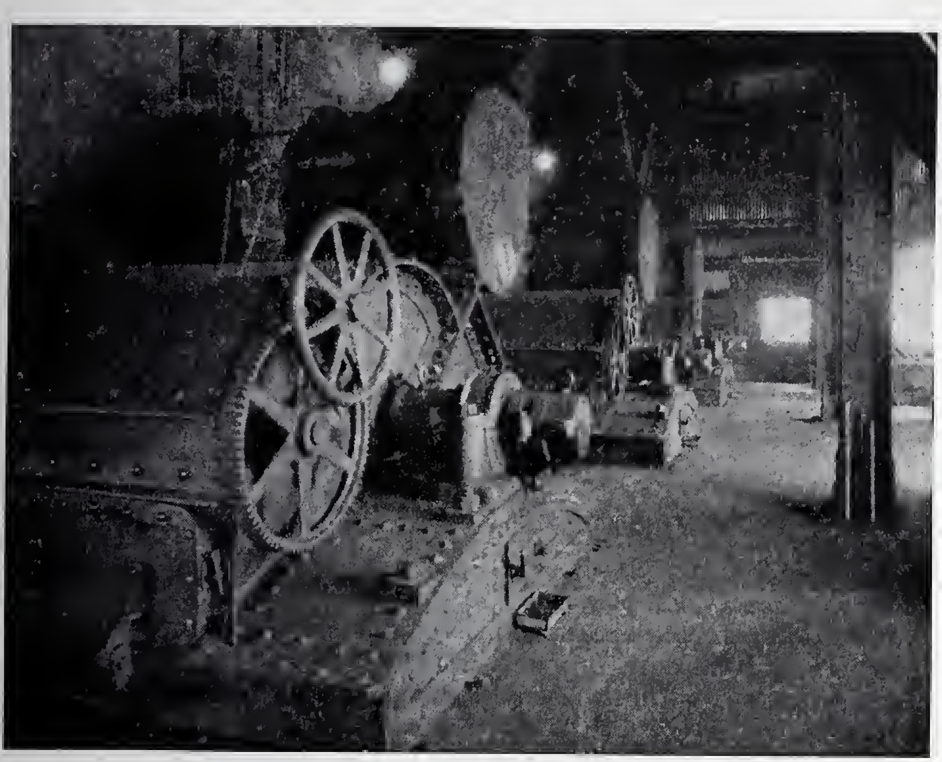

FIG. 30.—Installation of Three Hammermill Crushers.

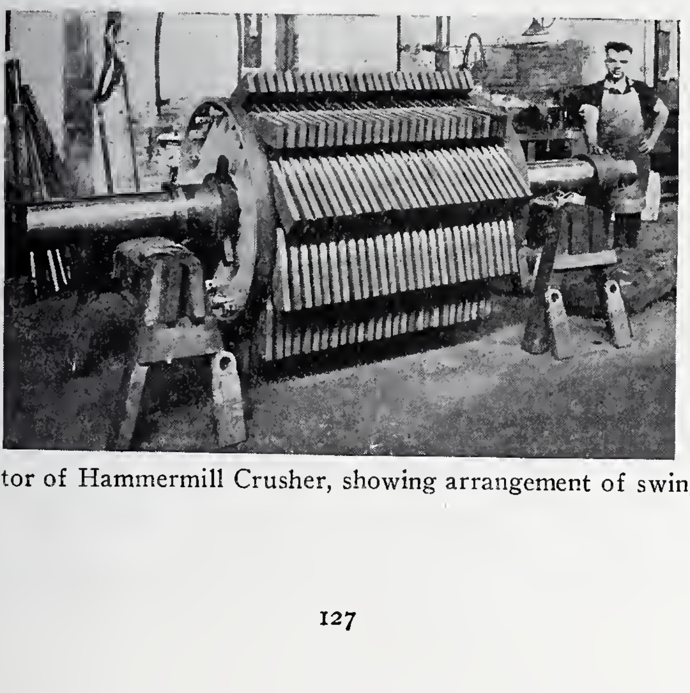

FIG. 31.—Rotor of Hammermill Crusher, showing arrangement of swing-hammers.

it into the oven and tend to weaken the coke structure in spots. On the other hand, such weakening of the lump structure would result only in more breakage to small pieces, not relatively a serious defect, while pulverizing of the pieces of slate in the coal would disseminate the impurity and bind it permanently in the coke. When only one kind of coal is being used, there appears to be little or no advantage in pulverization. Coke density and structure—especially with high-volatile coal—is improved by the compactness in the coal charge imparted through coarser crushing.

Quality of Coal for By-Product Ovens.

Coking Quality. Owing to the mystery surrounding still the mechanism of coke formation from coal, and the bearing of coal composition thereon, little can be said in explanation of the variation in coke quality obtained from different coals. The fact remains, however, that, entirely independent of ash or sulphur content, fineness of division, or conditions attending the coking operation, there is an influence of the organic composition of the coal substance, affecting the density, porosity and hardness of the coke and the strength of its cell walls. This matter is discussed in more detail in another chapter and it need only be said here that careful study of this factor in each individual case, mainly by oven trials of varying coal mixtures and of each available coal alone, will pay well for itself in improved coke quality and in gains attending application of the coke.

Much can be done to influence coke quality by regulation of oven temperature, oven dimensions, coking velocity and fineness of coal, but the nature of the coal itself remains the dominating factor. Degree of deoxidation by geologic aging of the coal bed, manifested in relative oxygen content in the dry ash-free coal, is perhaps the most useful element in the decision of coking quality. Coals of relatively low oxygen content (excluding anthracites) make as a rule the best cokes. If a coal contains more than 8 per cent. oxygen on the dry ash-free basis it will ordinarily not make a good commercial grade of coke. From the quantities of oxygenated decomposition products, *i.e.*, CO_2 and water, formed from the coal in the small-scale coking test, a similar judgment may be formed, without an analysis to determine oxygen in the coal.

Volatile matter in the coal mix, for best results in coke quality for metallurgical purposes, should be between 29.0 and 34.0 per cent. on the dry, ash-free coal. The low volatile coals added in the amount of 10-20 per cent. improve the strength and porosity of the coke.

Moisture, Ash, and Sulphur Content. These features of coal quality have been discussed under Coal Washing (pp. 116-8). Moisture, whether in the superficial form or as an inherent part of the coal substance, has an influence favorable to increased ammonia yield in coking. It may be considered, therefore, as desirable up to a limit, say of 7 per cent. in the coal. As previously mentioned, a greater amount of water is likely to injure the oven brickwork. Excessive ash content is said to weaken the coke structure and retard combustion in the blast furnace. Cooper[15] claims to have noted a marked improvement in physical quality of coke when the ash was reduced from 12 to 7 per cent. in the coal from which derived.

Chlorides, such as common salt, in the coal, have a deleterious effect on the oven linings, especially if these are of clay brick. J. W. Cobb[16] states that in British coke oven practice chlorides in the coal in excess of .05 per cent. (as NaCl) cause rapid wasting away of the walls due to the formation of sodium-aluminum-silicates.. This action is less serious upon silica brick. Chlorides, however, are also objectionable in causing formation of ammonium chloride which volatilizes, and corrodes, or clogs, the valves and pipes of the system.

Fineness of the coal, in its effect on coke quality and oven charges, has been discussed earlier in this chapter (page 126). Very friable coals which readily form impalpable dust have a tendency to cause trouble from clogging of ascension pipes and collecting mains.

Charging Coal to the Ovens.

The pulverized (or crushed) and mixed coal is carried by conveyors to storage bins above and between the oven batteries. Each of these bins has a capacity large enough for 24 to 48 hours' run of the ovens which it serves. From the hopper bottoms of the bins the coal is drawn into the charging car (Figure 32), propelled by motor, on rails along the top of the batteries and under the coal bins. Each charge is weighed in the car at the bin just after filling.

The charging car or "larry" holds from 10 to 16 tons (one full oven charge) in four hopper-shaped compartments, one for each charging hole in the oven top. The bottoms of these compartments taper to the size of the charging hole, and can be brought very close thereto so as to avoid spilling. The charge drops into the oven quickly (within a few seconds). The charging larry is not allowed to stand over the charging holes long enough to get hot, since a hot larry placed under the coal bins to receive a new charge would involve danger of inflammation in the bins.

It is of importance to successful operation that each oven be charged evenly and *full.* After the coal is dropped into the oven its surface is levelled by a leveller-bar on the pusher machine drawn back and forth over the coal by a motor. The bar enters the oven through a small chuck-door above the main oven door.

Careful loading and weighing of the larry car and its coal charge accordingly is of large influence on the regularity and smoothness of oven operation. Sufficient coal should be in the larry to fill the oven completely to the height of the leveller bar, but no greater amount, since any excess will be drawn out by the bar and wasted. Full and even charging makes for good yields and full production, and tends to prevent destruction of by-products by over-heated tops. The leaving of unnecessary space in the oven tops not only increases the heated surface over which the gases pass, but lowers also the speed of flow of the gas, a more serious factor promoting thermal decomposition of valuable gases and by-products.

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[15] G. Stanley Cooper, "By-Product Coking," Benn Bros., London, 1915, p. 9.
[16] *J. Gas Lighting,* 133, 684 (1916).

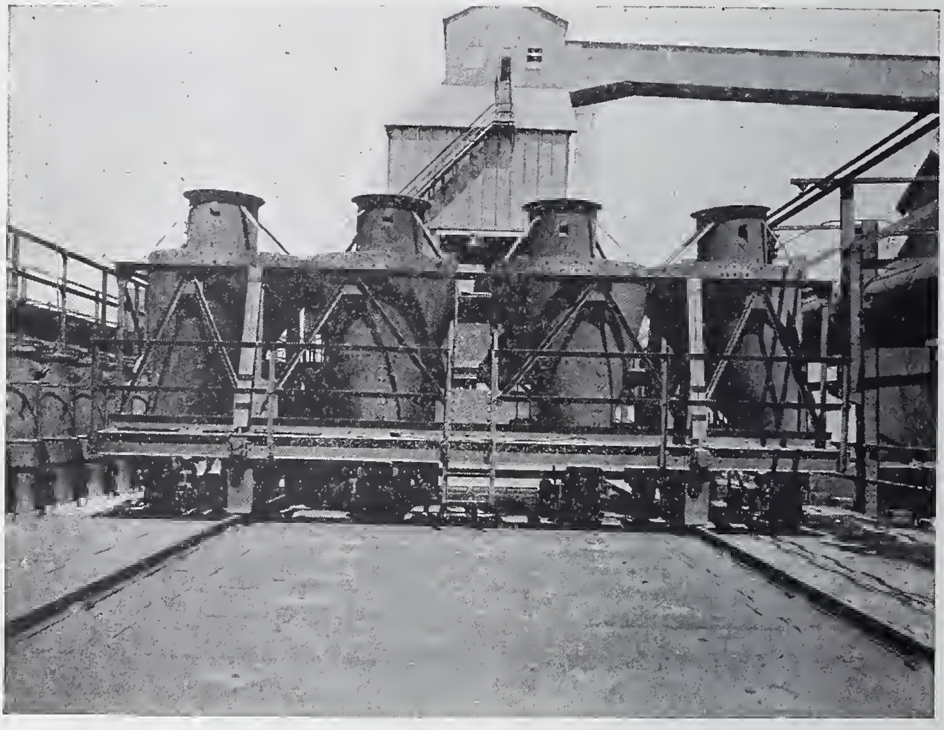

Fig. 32.—Larry, or Coal Charging Car, on Top of Oven Battery.

The oven doors are extracted and replaced by means of electrically operated machines (see Figure 33), moving along the battery on either side, or they may be lifted vertically by hydraulic power. The door machines on the pusher side are ordinarily borne by the pusher carriage, since the one operation immediately precedes or follows the other. The doors are clamped, or latched, in position and carefully luted so as to remain tight, and withstand the pressure of the solid coking mass which expands during part of the period of coking. The luting is done with a specially mixed clay or loam (containing 5-10 per cent. of coke dust or sweepings and a large proportion of old recovered luting which reduces the shrinkage). Clay carriers, or movable platforms to facilitate the luting operation, are pushed along the track on both sides of the battery.

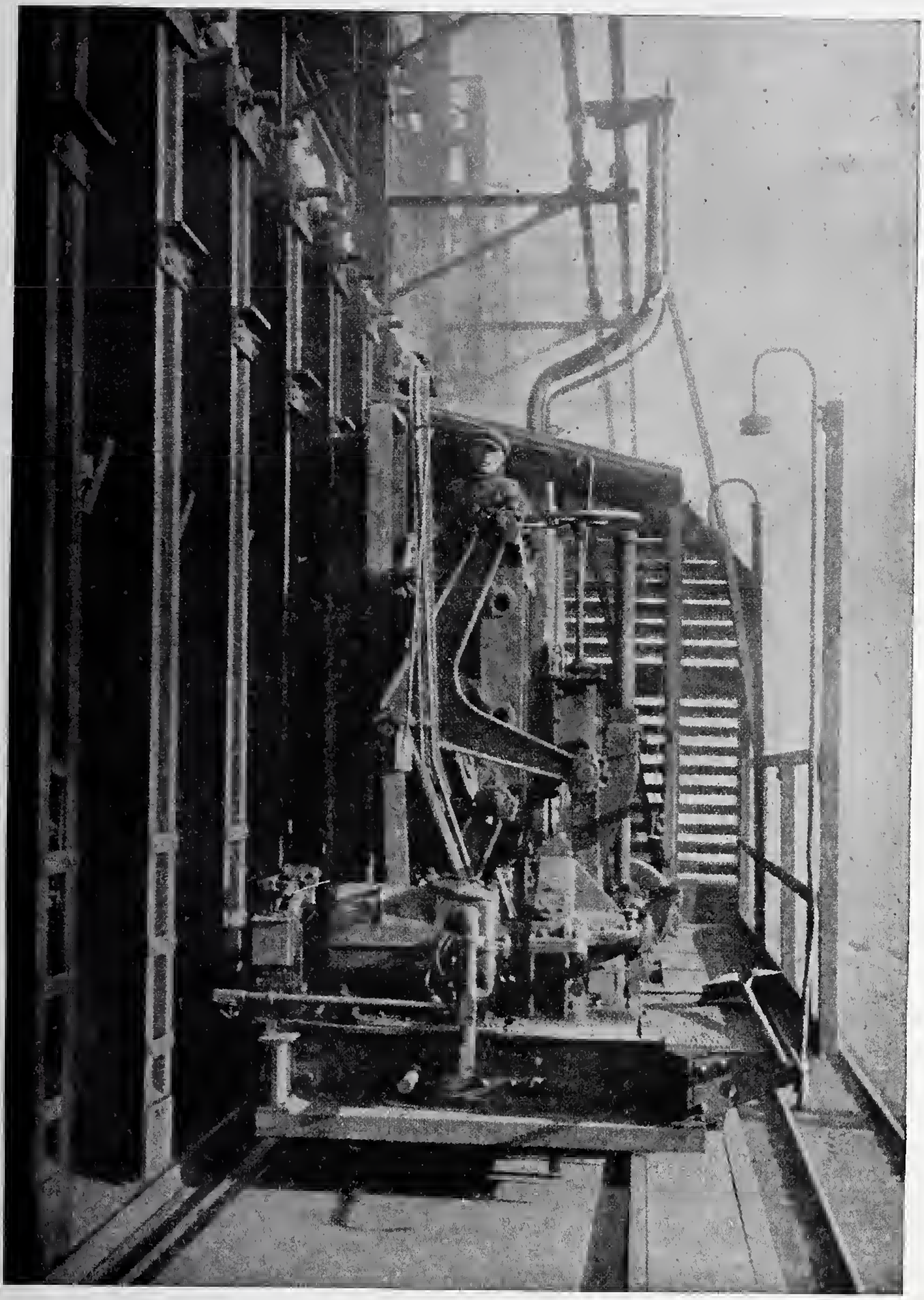

FIG. 33.—Door-Lifting Machine (on coke discharge side of battery).

[illegible]

Compressed coal charges or blocks of coal of the size of the oven, formed from crushed coal in a compression machine travelling along the battery at one side, have been used in British and other foreign practice. It is claimed that they yield coke of improved hardness and density, with coals of high volatile matter. In America these machines have not been found necessary since coke of requisite quality is made from high-volatile coals and mixed coals by careful attention to suitable choice of coals to be mixed, the fineness of crushing and the temperature conditions in the oven.

Withdrawal of Gas and By-Products to Recovery Apparatus.

The gas from destructive distillation of the coal in the oven, together with entrained liquid particles of water and tar and solid particles of coal dust, "carbon," etc., passes upward through the ascension or uptake pipe, a single outlet, generally near the pusher-side end of the oven. Placing of the outlet at or near the center of the oven has been proposed, and, in fact, practiced in some installations. It has the advantage of reducing the travel of the gas and by-products over heated surfaces within the oven.

Uptake pipes (Figure 34) are made of cast iron and are of ample size, often 15-17 inches in diameter. They become coated with carbon and hard pitch, which is periodically removed by a mechanical swab or scraper, inserted through the top, and, in modern installations, carried on a travelling support with crane and winch, running along the battery top. This carbon should not be left on the floor when a new charge is placed in the oven.

The gas is drawn, by regulated suction, through the inverted U of the uptake, into the horizontal common collecting main of the battery. This is placed well above the battery transversely to the ovens. It may vary from 30 to 60 inches in diameter. Two mains are provided when "gas separation" is practiced, i.e., the dividing of the run of gas obtained during the carbonizing period, into two parts, according to change in quality after a certain interval in the run (see further, page 134). Pitch traps are installed in the main usually at either end, to facilitate removal, by suitable tools, of the heavy pitch collecting therein.

Tar and gas-liquor—the latter an aqueous mixture charged with ammonia and its compounds—are withdrawn by pumps as they collect in the bottom of the main, and are in part recirculated to cool and flush the main (see pp. 282 ff.). The uptakes and collecting mains may become overheated as a result of combustion of gas, *within* the oven and uptakes, when air may be accidentally admitted through leaks in oven walls or at the jambs. Such overheating increases the formation of naphthalene and carbon by decomposition of the gas, and also thickens the tar in the main by distillation of its light oils. The result often is clogging of the pipes and valves by the increased pitch.

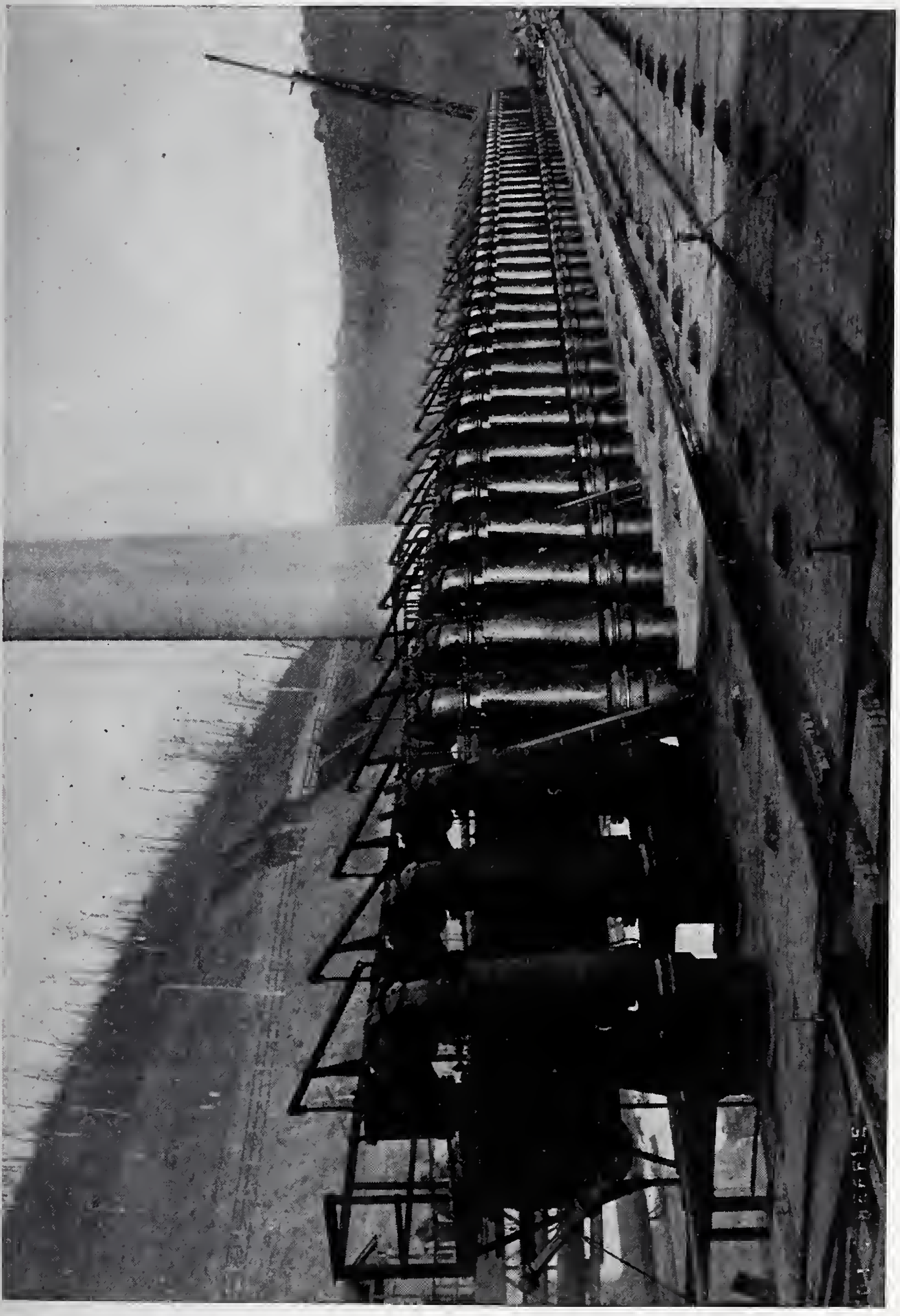

Fig. 34.—Top of Oven Battery, showing uptake pipes and collecting main (Semet-Solvay ovens).

Gas and by-products pass from the collecting main, under the pull of the "exhauster," through "cross-over" or "suction" mains (shown in Figure 1, page 22, to the condensers and scrubbers in the by-product building. More detailed description of by-product apparatus is presented in Chapter 11.

Gas Governors. It is essential to good operation that uniform and finely controlled pressure be maintained within the ovens and the collecting main. If pressure is too great there is a loss of gas through the brickwork, and if it becomes negative even in slight degree, air may be drawn in, diluting the gas and causing combustion within the oven. A difference of one millimeter of water pressure may seriously affect oven operation in this manner. Ordinarily, the best practice maintains neutral pressure within the oven.

To this end, not only is the speed of the exhauster in the by-product building regulated in accordance with the reading of pressure gauges on the incoming gas lines, but in addition (to be seen in Figure 1, page 22), *gas governors* are provided on the suction main, automatically regulating the pressure therein and in the collecting main, by control of a valve. Governors of various designs are used, some of them very delicate in their control, capable of overcoming in large measure the "surge" or the over-running of the desired point in effecting a change, this being a common fault with these instruments. As pressure becomes too great in the collecting main, the governor operates automatically to open slightly a "butterfly" valve, permitting greater outflow of gas. Usually a second valve in the main in advance of the governor valve is provided whereby rough regulation by hand is secured and more delicate control permitted in the governor.

Gas Separation. At many by-product coke plants where part of the gas is furnished to cities for public distribution, it has been found advantageous to provide two collecting mains and two complete sets of by-product recovery apparatus, so as to shift the flow of gas at a certain point in the run from the "rich" main to the "lean." The first half of the carbonizing period produces a richer gas than does the last half, although the latter gas is an excellent fuel and serves very well for use in the oven-heating flues. The rich gas has greater illuminating power and heating value per cubic foot than the lean, the difference being with good coal approximately 100 British thermal units.

The more modern plants furnishing gas to cities omit the practice of gas separation, since a requirement of minimum illuminating power in the gas is now rare, and the heating value or B.t.u. requirement has very generally been lowered. The straight run of coke oven gas after debenzolizing may easily be maintained at 550-570 B.t.u. per cubic foot and, if desired, slight enrichment with the vapors of benzol or other light hydrocarbon oils in a simple apparatus may be practiced when at times it may be needed.

In the practice of gas separation the point chosen for the shift from rich to lean is often determined on the basis of the fuel gas requirement in the oven flues. Sufficient pressure must be maintained in the lean-gas holder properly to fire the oven flues, and the remaining gas in the run is separated as "rich."

Coking Time and "Coking Velocity." An important factor in coke-oven operation and one frequently quoted in descriptions and comparisons of plant operations is the coking time, or the period required to complete the coking of a charge. Technically, for purposes of computation of output, or of total coal coked per day, it must be considered as the gross interval of time from the beginning of one charging operation to the beginning of the next, although the true or net coking time does not include the period in which the oven is empty following its discharge.

The "coking time" is one of the important factors determining the capacity of the plant and the operating and overhead expense per unit of output. It may be varied by regulation of oven temperature, and is, in fact, affected by a number of factors, viz.:

(1) Temperature of the oven walls.
(2) Width of the oven.
(3) Kind of coal.
(4) Amount of moisture in the coal.
(5) Fineness of the coal.

Comparison of the coking times at different plants is accordingly futile unless these various factors are taken into account.

Coking of the charge proceeds from the walls of the oven toward the center, and the "coking velocity" may be defined as the distance travelled per unit of time by the inner line of completely coked coal toward the center of the charge. It is measured practically by dividing the oven width, in inches, by the "net" or actual coking time in hours. (Strictly this is twice the true velocity, since the coking proceeds from both walls inward and the coked zone travels only half of the oven width).

The velocity decreases as the coking proceeds, because *the intervening layer of coke and partially coked coal is a very poor conductor of heat.* In all of the industrial coal carbonizing operations this fact is of tremendous importance, since it necessitates maintaining a wall temperature materially higher than the coking temperature, in order to secure practical operating capacity. A narrow oven gives greater coking velocity than a wider oven of the same wall temperature.

The average coking velocity in the modern American by-product oven is about 1.0-1.2 inch per hour. In other words, a charge of 18 inches average width is coked in 16 to 18 hours. In the "new type" Koppers ovens 13¾ inches in width, a coking time of 10 hours has been attained, thus showing a coking velocity of 1.375 inches per hour. Such velocities are only to be obtained in ovens built of high grade silica brick, which can safely be heated to the high temperature required.

The velocity is dependent also, as before stated, on the kind of coal, its content of water and the degree of fineness to which it has been crushed. These things affect the amount of heat carried away in the oven gas and vapors, and the facility with which heat penetrates the carbonizing mass.

Conditions Limiting Oven Dimensions. Economically, as regards operation and capacity, the practical width of a coke oven is limited by the factor above named of low heat conductivity in the coking mass. Ramsburg and Sperr[17] clearly emphasize this relationship as follows: "It becomes apparent at once, in a comparison between a 16-inch oven and a 20-inch oven, that the following is true:

"(a) With the same temperature of wall the average velocity of coking in the 20-inch oven will be less than in the 16-inch oven, and the time required to coke the 20-inch oven will be more than proportionally greater than the 16-inch oven.

"(b) To coke the 20-inch oven in the same time as the 16-inch oven, the wall temperature must be increased very markedly.

"(c) To coke the coal in the two ovens at the same average rate, the wall of the wider oven must be considerably hotter than the narrower one.

"(d) With the same wall temperature, more coke can be made per day in the narrower oven than in the wide one.

"(e) To make the same amount of coke per day, the wall temperature in the 16-inch oven would be lower.

"Four points are of great value in this connection:

"1. Overcoked material is of less value in a furnace than a greener coke.

"2. The wider the oven the more overcoked the outside layers will be and the larger the proportion of overcoked material for a given output.

"3. The production of by-products is enhanced by reducing the wall temperatures.

"4. The life of oven brickwork is increased by being operated at lower temperatures.

"There is no doubt among those who have been acquainted with the wider ovens that the narrower oven has the following distinct advantages:

"1. Less sponge in the coke.
"2. Better coke from the same coal.
"3. As good coke from higher volatile mixtures.
"4. Higher yields of tar, ammonia, and benzols.
"5. Lower temperatures for the same coking velocity."

The important fact in this connection is that as coking proceeds the velocity becomes more and more retarded by reason of increasing resistance of the widening zone of coke, the heat conducting mass, and a limit of oven width is therefore reached, beyond which it is uneconomical to go, as the authors above quoted have shown.

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[17] "By-Product Coke and Coking Operations," by C. J. Ramsburg and F. W. Sperr, Jr., *Journal of the Franklin Institute* (1917), 391-430, especially pp. 396-7.

D. W. Wilson[18] has investigated this subject mathematically on the basis of experimental data secured in Semet-Solvay coke ovens, and has deduced certain constants to be used in an equation correlating oven width and coking time.

Further experimental data along this line are given by A. Ruehl.[19]

The choice of width of oven is influenced also by the kind of coal to be used. The higher volatile coals and those of higher oxygen content yield better results in the narrower oven. A number of factors enter here, the effect of overcoking of these coals, the importance of preserving by-products, and other influences of coking velocity on coke quality not as yet thoroughly understood.

As to *length* of oven, the principal limiting factors are imposed by mechanical or structural considerations, and those of operating convenience. Theoretically, as far as the process and its products are concerned, in order to increase capacity, the oven might be made longer than in present average practice. But there is a limit set by impaired strength of the oven wall as its length is increased, particularly in respect to the resistance offered to the strain of discharging the mass of coke. Increased length of pusher ram and increased ground area for pusher travel with the longer oven are pertinent practical considerations.

Furthermore with vertical flued ovens having a horizontal flue near the top to carry off the gases of combustion from one half of the row and direct them downward in the other half, the length of oven is restricted by the limitation of this flue in capacity.

With the horizontal-flued ovens, the length is limited also by the requirement for uniform heats throughout the flue length, gas being supplied only at the ends of the various flues.

The plant of the Carnegie Steel Co., at Farrell, Pa., built in 1903, comprised 212 ovens of the Otto-Schniewind type, 43 feet in length, 7 feet high and tapered in width from 20½ inches to 17½ inches, this oven having been 10 feet longer than the usual examples of this type. Experience with this installation in respect to the yield of surplus gas per ton and capacity in coke per day, was not favorable to the longer ovens. On the other hand, recent Koppers installations have been made with ovens of nearly 40 feet in length and good results obtained. A new installation is in fact under construction for The Carnegie Steel Co. at Clairton, Pa., in which the ovens are 40 feet 4 inches long.

Increase in capacity of ovens is likely to be more economically developed and more practical through increase of height than through increase of length or width. For a given increase of cubical content there is incurred, by this method, a smaller increase in construction cost than by increase in length. Operating results, also are more favorable. The height of horizontal-flued (Semet-Solvay) ovens built in this country has steadily increased from about 6 feet in the original "3-high" oven (3 heating flues on each side) built at Syracuse in 1893 to 12 feet or more in the 16-ton modern "6-high" ovens built at all of the Semet-Solvay installations in 1918-20. (See Figures 172-3, in Appendix for relations of oven capacity to dimensions.)

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[18] "Mechanism of High Temperature Coal Carbonization," by D. W. Wilson, Massachusetts Institute of Technology, a paper presented at Technical Session, American Gas Association, 1923.

[19] "Relation Between Width of Coke Oven Chambers and Coking Time," *Blast Furnace and Steel Plant,* February, 1923.

The vertical flued ovens are in some degree restricted in height by requirements for uniform heat distribution vertically in the flues and oven wall. But it is probable that the practical limit in this respect has not thus far been reached in the ovens built in this country. The Indiana Coke & Gas Co., at Terre Haute, Ind., placed in run in 1919 a battery of 30 Koppers ovens of 16 inches average width and nearly 12 feet height (inside the oven chamber), 2 feet higher than the standard practice with this type prevailing for a number of years previously. These ovens have been heated and operated successfully, using, in customary manner, a portion of the oven gas as fuel. It is claimed by the builders of this type that by use of producer gas for heating, or by introducing into the flues with the air and coke-oven gas, a certain amount of inerts in the form of chimney gas returned from the waste flues, the character of the flame can be so changed that a greater height of flue and of oven wall than that above mentioned can be uniformly heated. These matters are discussed in more detail in a later chapter.

Sub

Temperatures in Oven-Heating Flues. In some of the modern American coke oven plants, using high grade silica brick, temperatures as high as 2,500°-2,600° F., measured with the optical pyrometer, appear to exist in the hottest part of the heating flues. The temperature used on any plant is regulated to produce the rate of output desired, and depends also on the width of oven, kind of coal, etc. As an average of normal operation, this flue temperature at its highest point in modern plants may be said to lie between 2,350° and 2,550° F. The wall temperature (at the face within the oven) varies with the age of the charge, but is always somewhat lower than that in the flue, due to the fact of constant conduction of heat away from the wall to the charge.

As to the relationship of flue temperatures to coking time or to rate of coking it is hardly practicable to make a general statement. The influences of various factors such as oven width, kind of coal, relative degree to which coking is carried, etc., are many and varied, and render the relationship indefinite. The range of flue temperature, however, for ovens of 16-19 inches average width may be said to be roughly 2,150° to 2,550° F. for coking time of 24 to 14 hours.

Measurements by the Bureau of Standards in a test on Koppers ovens at St. Paul, Minn.,[20] showing the flue temperatures, when coking Illinois coal, are presented in Figures 35 and 36, reproduced from the Bureau of Standards Paper 137. These measurements were taken by thermocouples in the upper part of the 7th and 14th flues on the pusher side of the battery. They were, therefore, not at the hottest points. The ovens were 18¼ inches in average width and the coking time used was 19½ hours. The average temperature as measured was about 2,200° F. At the base of the flues near the burners, on the coke discharge side the temperatures would be found 150°-200° higher.

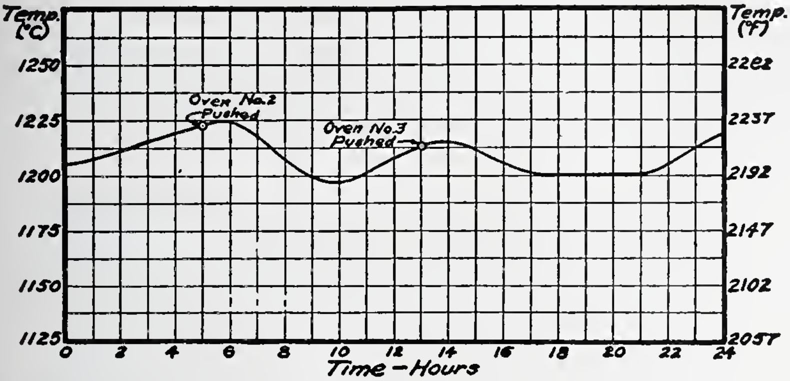

FIG. 35.—Average Temperatures in Heating Flues, Koppers Ovens, recorded in test by Bureau of Standards (upper part of flues, 7 feet below top of battery).

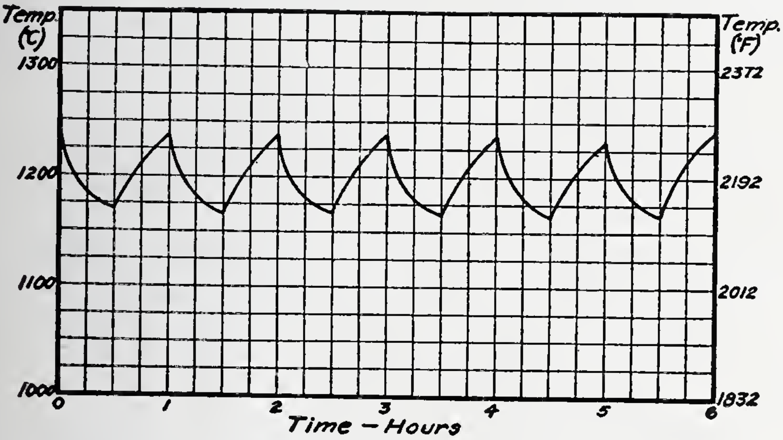

FIG. 36.—Typical Heating-Wall Temperatures, Koppers Ovens, as shown by tests of Bureau of Standards, illustrating effect of reversals.

In another plant of modern Koppers ovens, narrower in width (average of 17 inches with 2½ inches taper) and on shorter coking time (16 hours) flue temperatures were found ranging from 2,400° to 2,490° F. near the pusher side end and near the base of the flues (see pp. 144-6).

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[20] Technol. Paper 137, Bureau of Standards, 1919, pp. 18-19.

Temperatures in the Coal During Coking. Temperatures in the coal at various distances from the wall and at successive intervals during the coking period have been recorded by Hilgenstock, Simmersbach and others.[21] These temperatures vary with the conditions of operation, the flue temperature, the coking time, the width of oven, kind of coal, its content of moisture, fineness of division, etc., etc.

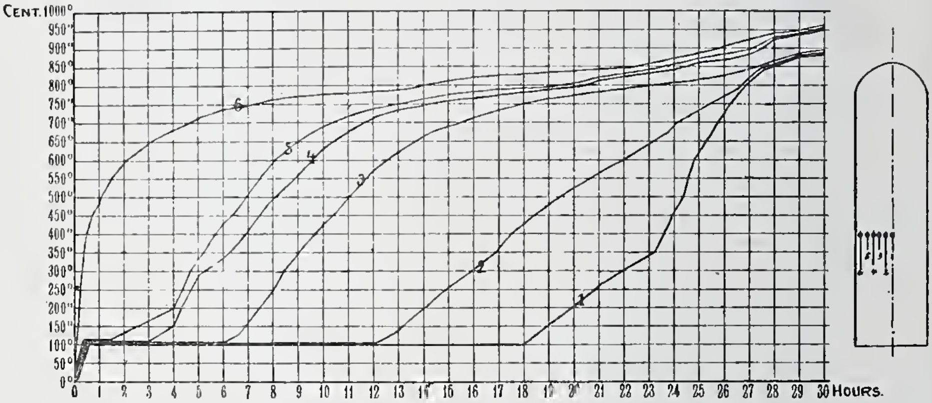

Fig. 37.—Temperatures at Different Points in the Coal Charge of a By-Product Coke Oven during the Coking Period (record by Hilgenstock in a German oven).

It is a general rule, however, that in the center of the charge the temperature for fully half of the coking period and often longer, does not go beyond approximately the boiling point of water.

At the center of the charge, in an oven of 18 inches average width the temperature reaches, at the end of the coking period, a maximum 500° to 600° F. below the temperature of the flues. In other words the average center temperature of the charge, at the end of the period, is about 1,800° F. when the flue temperature is at an average of 2,350° F. There may be a greater differential than this with certain kinds of coal, or with coal of high moisture content.

[21] R. W. Hilgenstock, *Journal für Gas-beleuchtung* 45, 617-21 (1902), giving a chart of curves which show variation of temperature at 6 different points in the cross section of a Coppée coke oven, 19½ inches wide on 30 hours' coking time. This chart is frequently quoted in discussions of temperature variation in the coal charge, and has been reproduced with proportionate adjustment to other coking times and oven widths. (See Figs. 37-38, p. 141.) F. Schniewind, *Iron and Coal Trades Review*, Oct. 30, 1903; Simmersbach, O., *Berg- und Hüttenmannische Rundschau*, 1913, p. 157; also a second set of measurements by same author, *Stahl und Eisen*, 34, 954-8 (1914); R. S. McBride and W. A. Selvig, Technologic Paper No. 137, U. S. Bureau of Standards, 1919, "Coking of Illinois Coal in Koppers Type Oven," pp. 20-21; Jos. Becker, *Blast Furnace and Steel Plant*, 10, 575-583 (1922), "By-Product Coking, with particular reference to New Combination (Koppers) Oven."

In a tapering oven there is a difference in temperature between the wider end where coke is discharged and the narrower pusher-side end, the latter temperature being higher by 100°-150° F. There is a differential also in the temperature near the oven walls and that at the center, approximately 100°-150° F.

In the chart (Figure 38) showing an adaptation of Hilgenstock's measurements (made on a 19½-inch Coppée oven on 30 hours coking time) to an oven of 18½ inches width and 21 hours coking time, the trend of the curves is to be noted. No. 6 taken at a point close to the wall, rises quickly through the range of the fusion of the coal (400°-550° C.) and then gradually to the maximum where coking is complete. Nos. 5 and 4, about 4 inches and 5½ inches respectively, from the wall, remain for 2½ or 3 hours at scarcely above the boiling temperature of water, after which they rise somewhat less rapidly than No. 6 through the coal fusion range, and then assume the same gradual rise to the maximum. The gradual character of the rise in this zone of the oven is due, in considerable degree, to the passage of vapors from the carbonizing zone through the porous mass of coke that lies in the outer parts.

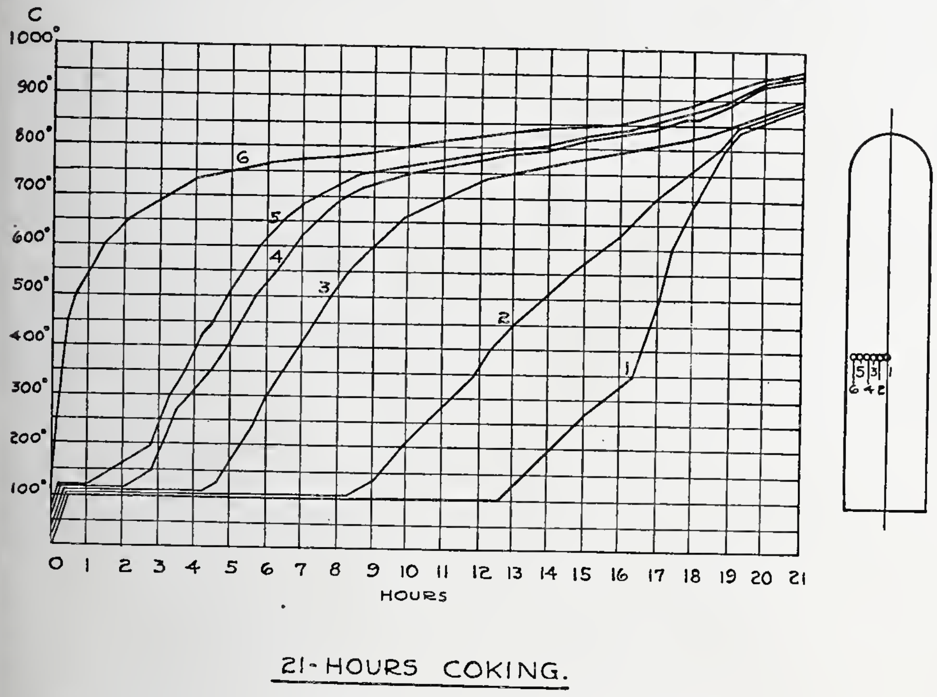

FIG. 38.—Temperatures at Different Points in the Coal Charge of a By-Product Coke Oven during the Coking Period (adapted from Hilgenstock's records, Fig. 37, to fit an oven of lesser width on shorter coking time).

Nos. 3, 2, and 1 (in the inner zone) remain relatively a longer time unaffected by the heat of the walls (4½, 8½, 12½ hours, respectively), and then rise to the maximum more rapidly than did the sections in the outer zones. This is to be expected, from the fact that through this zone there passes less of the heat-absorbing volatilized products arising from the primary reactions of carbonization.

The progress of the contracting zone of fused coal toward the center becomes slower as coking proceeds, or in other words, the coking rate diminishes the farther from the heated walls the coking progresses (see also on this pp. 135-6). This is well shown on the temperature chart by the wider separation of curves 1, 2, and 3 representing the temperature rise at points in the interior region of the charge.

The oven used by Hilgenstock was on the slower coking time commonly prevailing in European practice and yet the final temperatures thus attained in the center of the charge were practically as high as the average of modern American practice where the coking time is shorter and the oven narrower.

Temperature at the Center of the Coal, Variation in. Simmersbach in 1914[22] measured the center temperatures (midway of the walls and of the height of the charge) at the pusher end, discharge end and middle, the oven being 33 feet long, 8½ feet high and tapering in width 18 inches to 22 inches. The coking time was 29 hours. The following are some of the temperatures reported, as obtained at different stages in the coking period:

TABLE 16.

SIMMERSBACH'S TEMPERATURES IN GERMAN KOPPERS OVEN.

	Pusher Side		Middle		Discharge Side	
	Deg. C.	Deg. F.	Deg. C.	Deg. F.	Deg. C.	Deg. F.
13 hours	130	(266)	100	(212)	100	(212)
19 hours	520	(968)	430	(806)	410	(770)
23 hours	955	(1,751)	800	(1,472)	590	(1,094)
29 hours	1,090	(1,994)	1,120	(2,048)	920	(1,688)

The difference of 306° F. between final temperatures at pusher end and discharge end is to be noted. So large a difference as this, however, is hardly representative of modern American practice. The taper in the modern ovens is usually less than in this test (4 inches), and means are provided also to supply at the wider end a greater amount of heat per unit of wall area than at the narrow end.

Becker's measurements,[23] some of which are quoted below, afford a comparison of American practice (in Koppers ovens) with the German. Becker reports center temperatures in the coal charges, 4 feet in from the pusher-side end, at three different levels, A, two feet above the bottom, B, 2 to 3 feet from the top of the charge (varying at the different plants where tested), and C, on a level with the center of the horizontal flue, i.e., near the top of the charge:

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[22] *Stahl und Eisen,* 34, 954-8 (1914).

[23] J. Becker, "Modern By-Product Coking (in Koppers Ovens)," *Blast Furnace and Steel Plant,* 10, 575-583 (1922).

TABLE 17.

J. BECKER'S TEMPERATURE MEASUREMENTS IN AMERICAN KOPPERS OVENS.

	Time	A	B	C
(1) Ovens of Providence Gas Co., Providence, R. I., regular type, width 15¾ inches-18¼ inches	18h. 20m.	1,800°	1,700°	1,560° F.
	19h. 20m.	1,870°	1,800°	1,670°
	21h. 12m.	1,930°	1,880°	1,800°
(2) Seaboard By-Product Coke Co., Jersey City, N. J., width 17 inches-19½ inches	23h. 26m.	1,890°	1,450°	1,353°
Ditto, using waste-gas return in heating flues...............	23h. 18m.	1,793°	1,607°	1,590°
(3) Chicago By-Product Coke Co., in "New Type" Koppers oven, width 13¼ inches-14¾ inches	10h. 30m.	1,850°	1,800°	1,675°

These temperatures are in general somewhat lower than those reported by Simmersbach, Table 16, (at pusher-side end, on completion of coking), in spite of the fact that the flue temperatures are somewhat higher than in the German practice. The German oven, on the relatively long coking time used (29 hours), is evidently overcoked at the pusher-side end, and thus secures a higher temperature in that part as compared to the American oven.

Becker's measurements at different levels in the charge show the effect of improvements in the heating system (both in structural design and in the kind of heating flame) on the degree of uniformity of heats—from top to bottom. The "New Type" oven, temperatures in which are indicated under (3) Table 17, makes possible, by its improved design wherein the horizontal flue is of smaller size and placed higher in respect to the coal charge (see pp. 194-200), a more uniform coking rate across the top and bottom of the charge—thus completing the coking (for a given width) in less time and raising the capacity of the oven (Figure 39).

In the older or "regular" type of Koppers oven, illustrated under (1) and (2), Table 17, there is a lag in the top part of the charge in reaching the requisite temperature of completed coking, and the charge either is pushed with some under-coked portions at the top, or is allowed to remain in the oven until the lower portions are over-coked, resulting in reduced output.

The effect of lengthening the heating flames by the addition of inert gases in the form of waste-gas returned is shown in the records for the Seaboard plant (under (2), Table 17), where by this expedient the temperature rise at the different levels is shown to have been rendered more uniform.

The inert gases by their high specific heat and the diluting of the oxygen in the mixture, retard combustion and lower the flame temperature *at the burner.* The heat of the flame is thus distributed more evenly from bottom to top of the flue (see also pp. 255-6).

The length of flame in the heating flues is affected also by the pressure on the fuel gas and the kind of fuel gas used.

Some unpublished results of temperature measurements in another plant of comparatively new American Koppers ovens have been furnished the author. These measurements are of interest due to the rapid coking rate used (1.0-1.15 inches per hour, the oven being 15¾ to 18¼ inches in width and on 16-hour coking time), and the con-

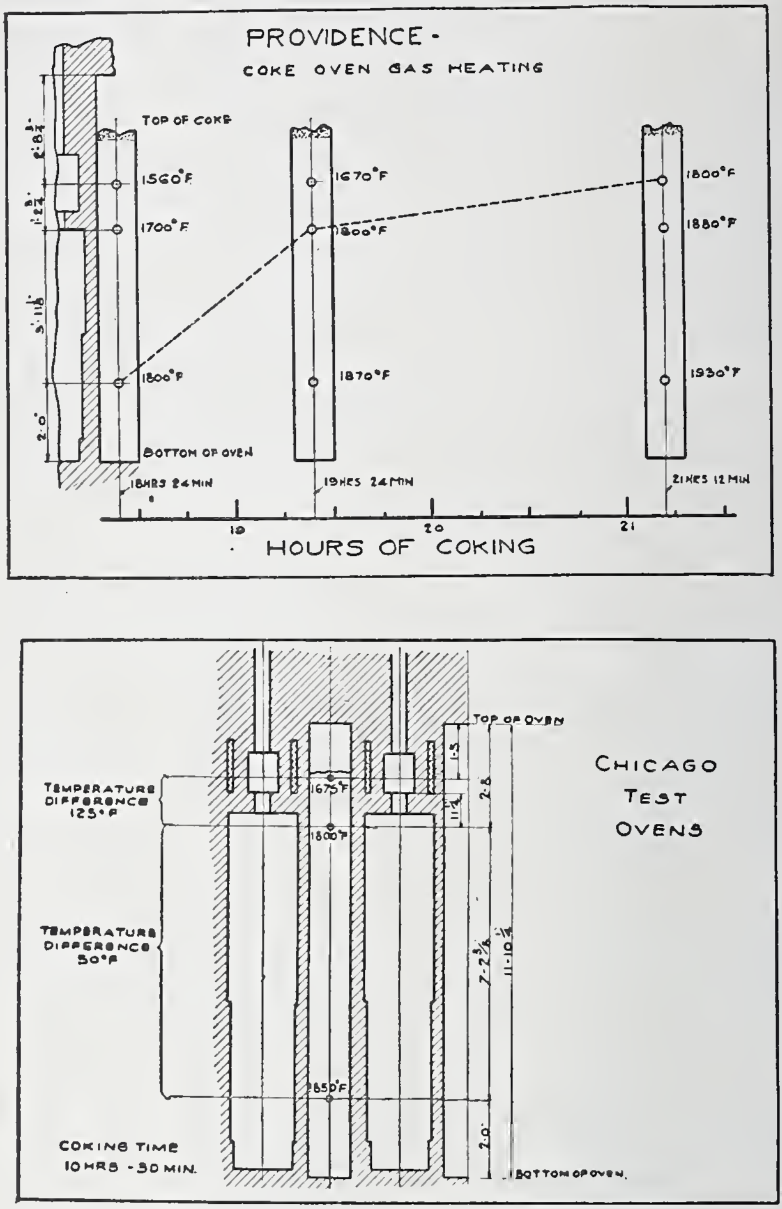

Fig. 39.—Temperatures in Center of Charge, at different levels, Koppers ovens, comparing "regular type" oven, at Providence, with "new type" oven, at Chicago (diagrams by J. Becker).

formity of the temperature curves (Figure 40) in general and of final temperatures in the charge, with those of Hilgenstock (Figure 37) on slow coking time.

Figure 40 shows these temperatures through the 16-hour coking period at 3 points in the cross section of the pusher-side end of the oven, midway in depth of the charge. No. 5 was 4 inches from the wall, No. 3, 6 inches from the wall, and No. 1 at the center. The flue temperature in this case averaged 2,395° F. The curves are very similar in shape to those of Hilgenstock—(Figure 37)—although in this case the center point (No. 1) attained the temperature of the initial fusion of the coal (350°-400° C.) in 11-12 hours whereas the corresponding point in Hilgenstock's measurements showed 16-17 hours due to the slower coking time.

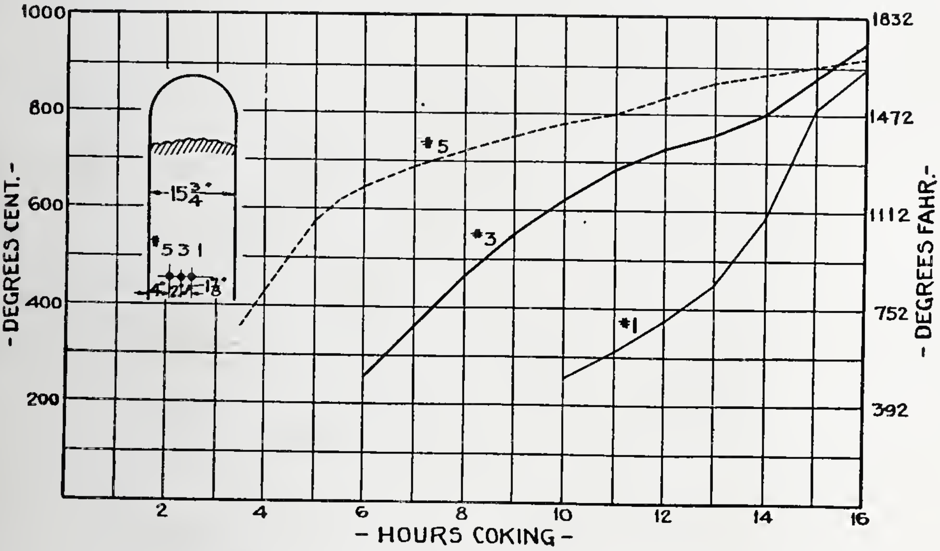

Fig. 40.—Temperatures at Different Points in the Coal Charge of Koppers Ovens (on 16-hour coking time, 17 inches average oven width).

In Figure 41 are shown the curves of temperature rise at this same plant in the center of the oven at different levels, near pusher-side end, with coking time the same, 16 hours. Conforming to Becker's records (pp. 143-4) for other Koppers plants, these readings show temperatures about 200° F. higher at points near the bottom than at a point near the top—when coking neared completion. This test showed considerably higher temperatures in the charge—at completion of coking, than did the test on the same plant recorded in Figure 40, although it was made in an oven of the same width under the same coking time. It is of interest to note that this may have been caused by the fact of the use of different coal in the mixtures in the two cases. The flue temperature averaged 2,488° F. for the test shown in Figure 41 or about 90° higher than in the other, while the difference in center temperature of the charge was at least 350° F. The charge apparently coked at a rate more rapid than would conform to the difference in flue temperatures.

The record of a test by the Bureau of Standards, in Figure 42,[25] shows temperatures in the center of the coal charge near the pusher side end, while coking Illinois coal on 19½ hours' coking time. The oven was a Koppers at the plant of the Minnesota By-Product Coke Co., St. Paul, Minn., and was of width, tapering, 17 to 19½ inches. The coking rate, therefore, near the pusher-side end, was slightly under 0.9 inch per hour. Flue temperatures averaged 2,300° F. The center of the charge appears in this case to have required 15-16 hours to reach incipient fusion of the coal. The kind of coal used has important bearing here.

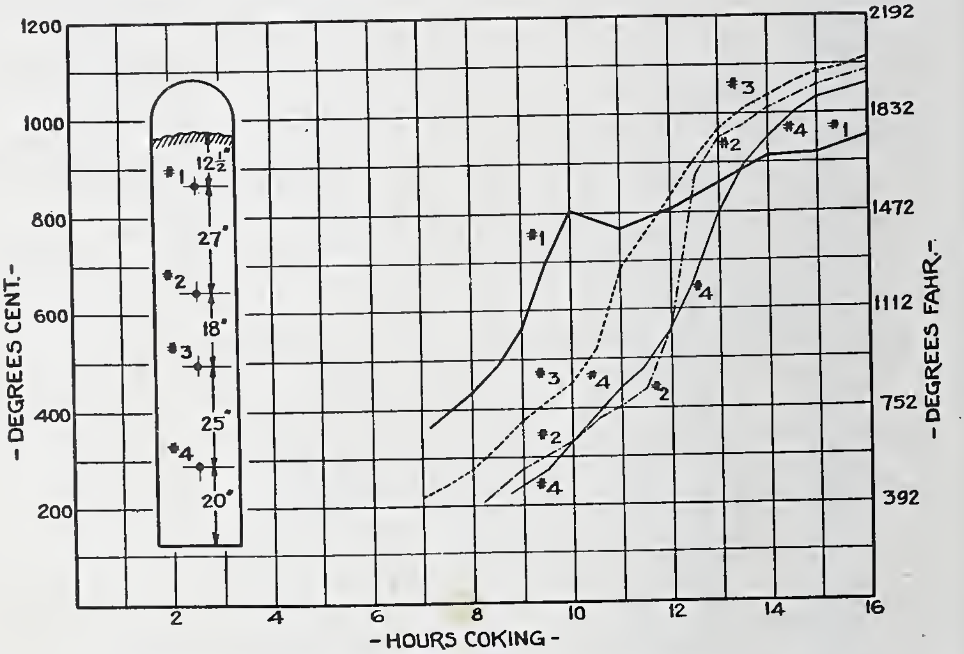

Fig. 41.—Temperatures at Different Levels of the Center of the Coal Charge, Koppers Ovens (on 16-hour coking time, 17 inches average oven width).

Temperatures in Oven-Tops, Uptakes, and Mains. Temperatures of the oven tops and of gases leaving the oven vary greatly with the conditions pertaining to each installation, the design of oven and heating flues, the tightness of brickwork and doors, and the method of operating the ovens.

The temperature in the oven tops usually lies between 750° and 850° C. (1,382° and 1,562° F.), the gases leave the oven at 600°-700° C. (1,112°-1,292° F.), and enter the collecting main at 300°-400° C. (572°-752° F.). The ascension pipe should never reach a red heat—even dull red—as this indicates excessive temperature in the oven tops, probably due to admission of air through leaks, and consequently undue decomposition of by-products. The temperature of gases entering the suction mains—to leave the battery—ranges from 150° to 200° C. (292°-382° F.).

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[25] Technologic Paper No. 137, Bureau of Standards, 1919, pp. 20-21.

A circulation of tar and liquor in the collecting main is maintained in such manner as to keep a temperature of 80° C. (176° F.) or less *in the liquor.*

"Cracking" or Decomposition of Gas and By-Products in the Oven. To excessive temperatures in the open tops causing thermal decomposition, there may be attributed very often a serious loss of values in gas and by-products. Undoubtedly, such decomposition occurs more or less in all ovens, and is promoted by increase of temperature and of open space in the part of the oven above the charge. The gas reactions occurring, influenced in accordance with physico-chemical laws by temperature, concentration, velocity of flow and time of contact with solid surfaces, act in important degree to determine ammonia yield, light-oil (i.e., essentially benzol and toluol) yield, nature of the permanent gaseous hydrocarbons produced, heating value of the gas, and the troublesome formation of naphthalene and other solids which lead to stoppages in pipes and valves.[26]

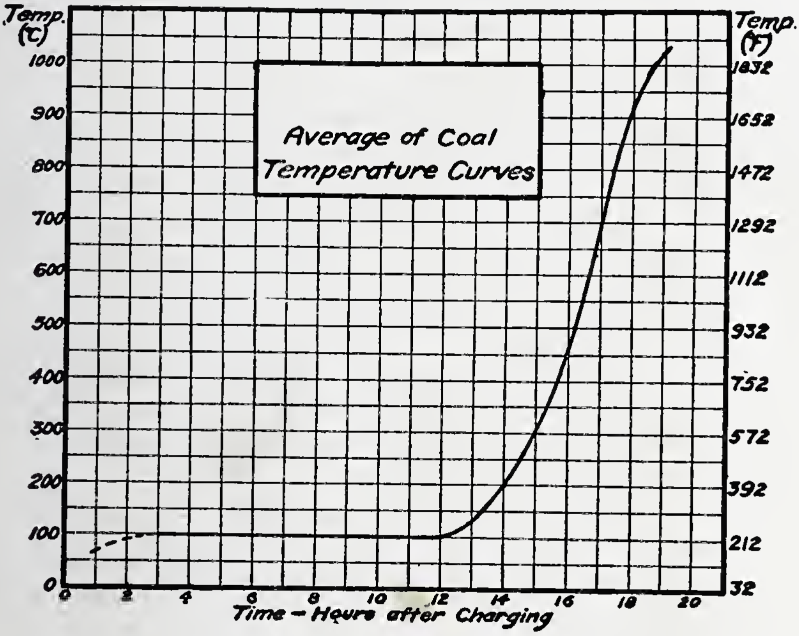

FIG. 42.—Average of Coal Charge Temperature Record by Bureau of Standards, in Koppers Ovens (18¼ inches average width, 19½ hours coking time).

Elimination of unnecessary space in the oven tops is a feature of modern development in oven designing. Only sufficient space is provided to accommodate the levelling ram and permit its ready operation in raking the coal so as to give a level surface to the charge.

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[26] See Chapter 11, pp. 317-21, 325-6, for discussion in detail.

Increase of heated open space in the tops not only offers greater surface of hot brick to the passing gases, but retards also their velocity so as to increase the time of contact and thereby the amount of thermal decomposition.

Course of Gas Travel in the Charge. The course of the gases and of the tar and other vapor-form products in escaping from the point of their origin in the coal, their initial composition when liberated, the progressive changes which they undergo, and the thermal conditions to which they are subjected while finding their way out of the oven, are matters of much importance in determining final results. They are treated more fully in another chapter in a discussion of the Theory of Carbonization (pp. 87-93).

The gaseous products do not pass entirely along the hot walls of the oven, nor do they find exit in any considerable amount through the uncoked center of the coal charge. The main portion passes through the coked and partly coked region in the charge, backward, toward the walls, from the advancing ring or shell of fused coal. It seeks the easiest passage—where the material is relatively porous and in some measure fissures have developed. Naturally, in paths of least resistance, much of these products seeks its egress along the open spaces where, near the wall especially, the hardened coke has drawn away a little to leave openings. But the principal portion passes upward and out of the charge through the coking mass without reaching the hot walls.

Much decomposition of the primary tars and gases, arising from the pasty fused layer of coal, takes place as these products pass through the heated zones. Carbon is deposited thereby on the coking material, not loosely as soot, but in a hard, cementing form which aids in strengthening the coke.

A small amount of gas and vapors, containing a large proportion of steam, must pass out through the inner core of uncoked coal. It comprises essentially the initial carbonization products, formed from the coal while being heated to the fusion or pasty stage, i.e., up to 350° C. This is relatively a very small part of the total gaseous products, and it undergoes little or no secondary decomposition until it reaches the hot open space above the charge.

O. B. Evans[27] has made, experimentally by examination of pressure and temperature conditions in the charge, a careful study of these relationships as they exist in the carbonization of coal in vertical gas retorts. His findings in general apply also to coke ovens. They support the conclusions outlined in the foregoing.

The fact that the tar from bulk carbonization of coal in vertical gas retorts and coke ovens contains very much less free carbon and highly-carbonaceous compounds than does the tar from the small thin charges

[27] *American Gas Light Journal,* 99, 338 and 346 (1913).

of horizontal gas retorts, shows that their vapors of decomposition do not pass entirely or even very largely along the highly heated oven walls, but rather in large measure through the moderately heated coking mass.

F. W. Sperr, Jr.,[28] outlines the course of the coke oven carbonization process, and the flow of the gases as follows: "The gases and vapors follow always the lines of least resistance and pass through the porous outer layer and up along the wall of the oven, instead of forcing their way through the viscous inner portion of the fused layer and then through the mass of coal. In passing through the highly heated porous layer, the hydrocarbons undergo a partial secondary decomposition, depositing part of their carbon on the cellular surfaces just formed. As the coking progresses, cracks or joints develop, perpendicular to the wall of the oven. These cracks form avenues of escape for a large percentage of the gases, hence the amount of deposited carbon is greater in proportion on the surfaces of the blocks than in the interior."

Variation in Composition of Gas as Coking Proceeds. As the coking of a charge in an oven proceeds, the gas evolved becomes thinner and of lower calorific value. The early gas has a higher content of

TABLE 18.

COMPOSITION OF THE GAS DURING CARBONIZATION (PER CENT. BY VOLUME).

Hours Coal Carbonized	CO_2	C_6H_6	C_2H_4	O_2	CO	CH_4	H_2	N_2	Min. Calorific Power (0° C. 760 mm.) Calculated per Cubic Meter
2	3.30	1.80	4.00	1.05	0.90	36.65	42.50	10.00	5,402
3	3.00	1.50	3.50	0.80	1.90	36.10	44.60	8.60	5,271
4	2.30	1.10	3.10	0.60	2.90	34.50	48.80	6.70	5,086
5	2.50	1.10	3.20	0.60	2.80	34.50	47.80	7.50	5,071
6	2.20	1.00	2.80	0.50	3.00	33.60	50.10	6.80	4,971
7	2.00	0.80	2.50	0.50	3.95	32.40	50.75	7.10	4,802
8	1.40	0.60	2.50	0.20	3.40	33.65	53.75	3.60	4,906
9	1.90	0.50	2.00	0.20	3.10	33.45	50.55	8.30	4,797
10	2.30	0.35	1.75	0.20	2.80	31.20	47.10	14.30	4,324
11	1.30	0.35	2.05	0.10	2.80	32.40	51.50	9.50	4,583
12	1.50	0.35	1.85	0.20	4.15	33.40	50.65	7.90	4,660
13	2.00	0.30	1.80	0.20	4.10	32.45	49.75	9.40	4,530
15	1.90	0.25	1.80	0.15	3.90	33.20	53.40	5.40	4,665
17	1.80	0.10	1.90	0.25	4.15	30.60	51.60	8.60	4,369
19	1.10	...	1.20	0.15	4.70	26.10	55.75	11.00	3,978
21	1.05	...	1.00	0.05	4.00	21.15	58.95	13.80	4,487
23	0.80	...	0 60	0.05	3.80	18.95	61.90	13.90	3,412
25	0.70	...	0.30	0.10	4.90	12.20	67.00	14.80	2,960
27	1.00	...	0.30	0.30	5.80	4.70	70.00	17.90	2,419
Heating gas	2.10	...	1.80	0.60	4.20	26.20	51.70	15.40	3,964

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[28] "American Fuels," by Bacon and Hamor, McGraw-Hill Co., New York, 1922, pp. 90-91.

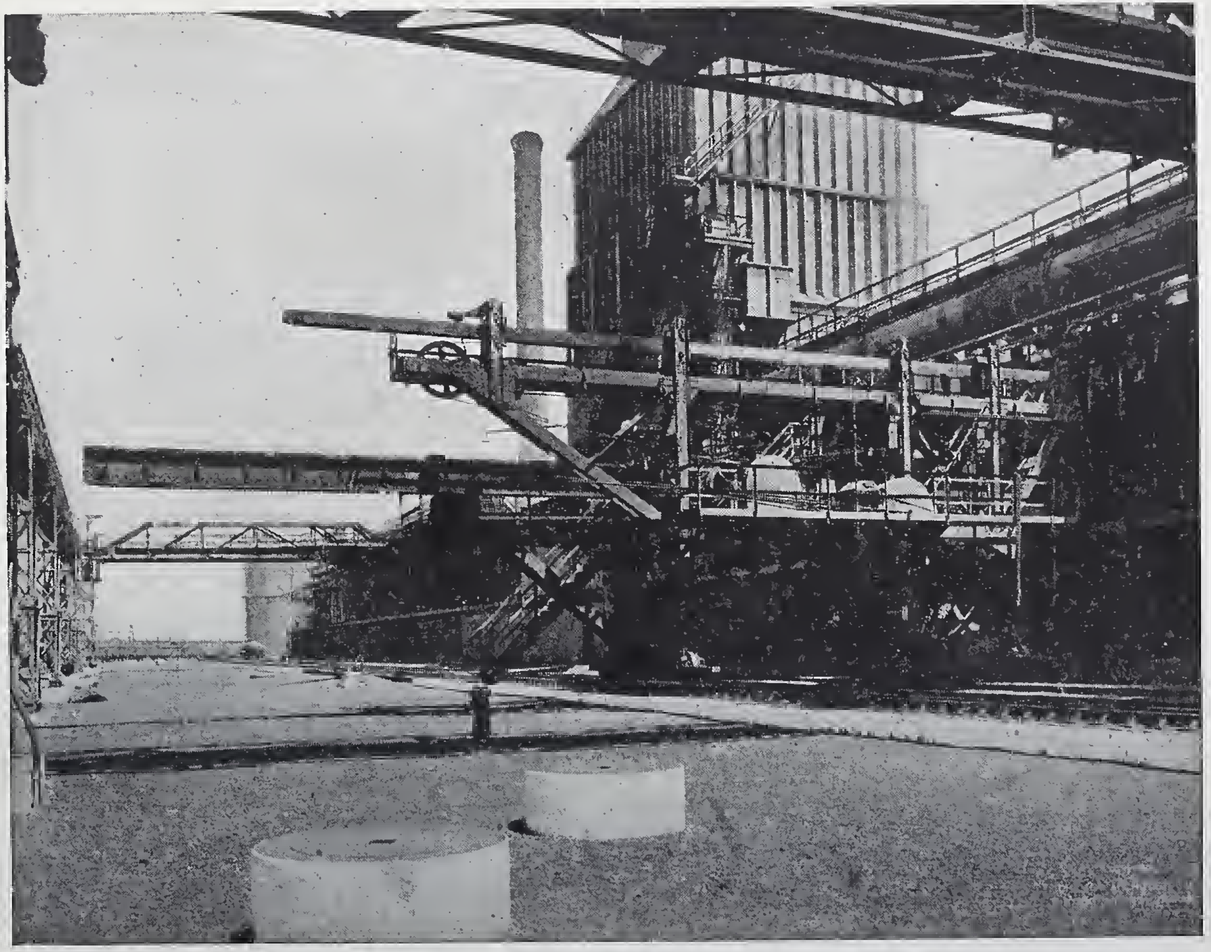


Fig. 43.—View of Battery of By-Product Coke Ovens, with Pusher Machine in Foreground.

hydrocarbons—particularly of those rich in carbon, and a lesser content of hydrogen, than has that evolved in the later stages.

This is to be expected from the fact of the gradually widening layer or zone of coke and partly coked material, heated to the "cracking" temperature of the initial vapors and gases. The hydrogen of the gas arises very largely from these secondary decompositions undergone in the passage through the hot coke.

Table 18, quoted from Bacon & Hamor's book "American Fuels," (*loc. cit. page 188*), gives the composition found in the gas from a by-product coke oven at successive intervals during the coking period.

Similar data from other sources are presented in Chapter 11, pages 316-17.

An interesting point to be noted in these records is the higher percentage of carbon dioxide in the gas during the early stages, with a more uniform, or in a measure an increasing, percentage of carbon monoxide. This shows that the products of early decomposition (under 350°-400° C.), known to be high in carbon dioxide and water, do not pass out through the hot coke layer or along the highly heated walls. If they did, the carbon dioxide would be decomposed to monoxide, and the latter would predominate in the resulting gases.

Card

Pushing Coke.

The entire coke mass in the oven is discharged (Figure 44) in less than one minute by a pusher ram driven by electric motor through the oven from end to end. The ram, motor and requisite gears and control are carried on a pusher machine which travels transversely from oven to oven along one side of the battery. This machine and the track on which it runs are necessarily of heavy construction, capable of withstanding the severe strain incident to pushing a mass of 10 tons of coke in a long narrow chamber. The *horizontal thrust* of the ram-head on the coke may reach 50,000 pounds, or even higher if certain abnormal conditions prevail, which increase the difficulty of pushing and cause so-called "stickers," aggravated often by careless operation of the pusher.

The Pusher Machine, illustrated in Figure 43, is of heavy steel construction, and carries not only the pusher ram and its motor, but the coal-levelling bar and motor, door-lifting machine and motor, and the traverse-motor for moving the machine along its track. An operator's cab is provided, so placed that he may readily see in both directions, may observe also the interior of the oven while pushing a charge, and is reasonably protected from the heat of the oven. An ammeter should be permanently installed in the operator's cab to indicate the current used in pushing, and circuit breakers must be provided to prevent too high an over-load on the motor or strain on the machine and the oven. A recording ammeter is frequently placed in the power house or sub-station to provide a continuous record of power used in pushing and levelling. If, however, such an instrument records the work of more than one machine, overlappings occur and there is little chance to isolate the record of any one operation.

Careless and *difficult pushing* is often the source of serious damage to the ovens. The oven walls are in this way subjected to sufficient strain to throw them out of line and cause them to bow or bulge, which in turn still further increases the difficulty of pushing coke and soon necessitates rebuilding of the oven. With ovens in good condition, walls straight and free of irregularities, with non-expanding coal mix and careful operation, the *maximum amperage* used (on 220 volt circuit), in starting the movement of coke, should not be over 200 and may be as low as 125 amps.

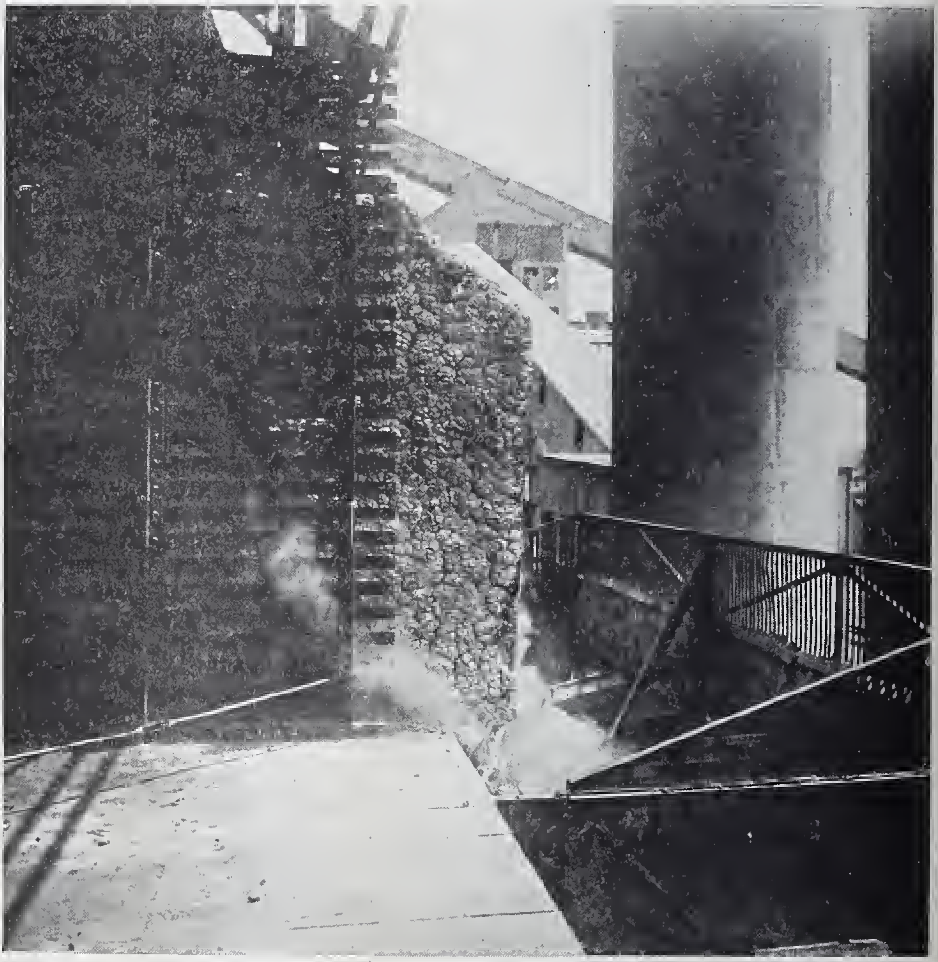


FIG. 44.—Coke being discharged from Oven, through Guides, into Quenching Car.

Many coals and coal mixtures tend to *expand* permanently in coking. Coals of less than 25 per cent. volatile matter are frequently in this class. Such expansion puts a strain on the oven walls and causes difficult pushing of coke. It must not be confused, however, with the swelling or flowing of the plastic coal at its softening temperature, an apparent or transient swelling, which occurs with all coking coals and may frequently be shown by imprints of the oven wall and brick joints on pieces of the finished coke. No definite relationship between the expanding quality and coal composition has been established, nor is there a reliable laboratory test to show definitely the expanding character. Expanding coals may be used successfully in by-product ovens in admixture with a sufficient proportion of a strongly shrinking coal but especial care is needed in maintaining regularity of oven operation, constancy of coal mixture and frequent attention to needed repairs in oven walls.

"Stickers" and Difficult Pushing may result from the following causes:

1. Distortion or irregularities in oven walls or floor.
2. Expanding coal (sometimes occasioned by incomplete or irregular mixing).
3. Over-coking, a practice which tends to make the coke mass crumble into small pieces, or collapse under the pressure of the pusher ram. A charge should not be allowed to stand or "soak" in the oven to become harder after completion of the coking process, since the temperature rises then more rapidly, endangers the brick-work, and makes pushing more difficult.
4. Under-coking in excess, very "green" charges being generally hard to push, although a slightly "green" oven is not difficult and the coke thus made is, by many users, accepted as of superior or equal quality.
5. "Bumping" a charge through careless operation, advancing the ram head rapidly against the charge.
6. Using a ram with too small or too low a head, causing the face of the coke mass to crumble.
7. Presence of scraps of brick, luting clay, carbon from standpipes, etc., on the bottom of oven at pusher end.
8. Irregular heats, causing dark low-heat spots or layers in oven and charge.

Pushing Schedules. Schedules for the order of ovens to be pushed are essential to regular, successful operation and good plant yields. They must be systematically worked out to suit local conditions, the number of active ovens, coking time, number of pushers, etc., and then be rigidly adhered to, if best plant results are to be attained. For example, *an oven must not be pushed when an adjoining one is empty,* since excessive strain is thus set up on the wall next the empty oven. An oven is best pushed when those next it are at a stage sufficiently advanced in the coking process to give their charges rigidity.

✓ The progress of coking in adjacent ovens, under a schedule of pushing wherein the succession of series of ovens is "by threes" (see below), is illustrated in Figure 45. (Koppers Co. drawing.) It is evident that under this schedule when one oven charge is ready for pushing, the next adjoining ovens are far from being at an equal stage of progress. Such a condition has a tendency to produce inequality of the strain on the two walls during the pushing, and an unequal rate of coking on the two sides. In those types of oven wherein the battery is built with separate sets of heating flues for each oven and a strong division wall standing between each two oven units, this risk is not incurred.

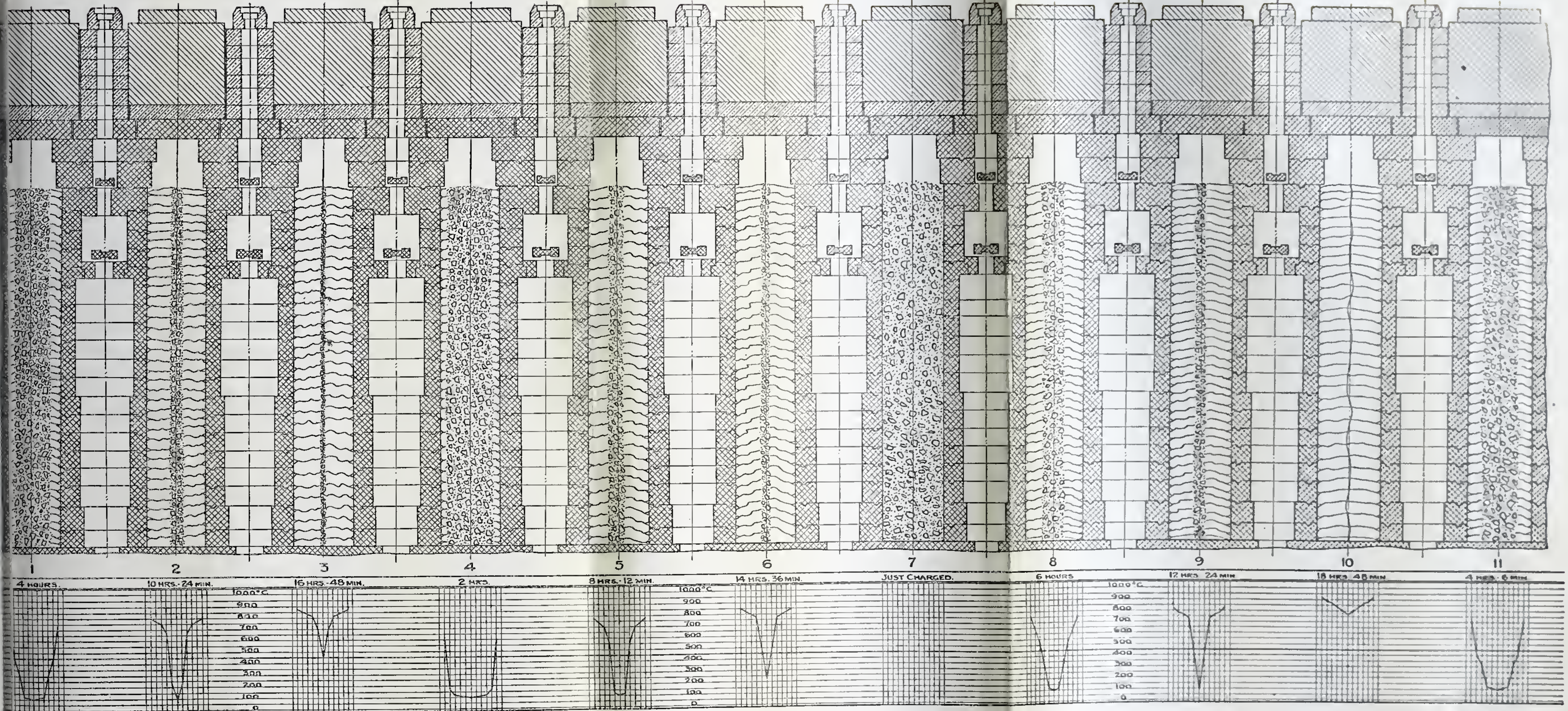
The "Three" Schedule. The ovens being numbered consecutively from end to end of the battery, the pushing schedule ordinarily follows

TABLE 19.

Example of Pushing Schedule by "Threes."

Two batteries, A and B, 60 ovens each, 3 series' interval, 18-hour coking time.

Oven No.	Time	Oven No.	Time	Oven No.	Time	Oven No.	Time
1-A	12.00 M.	10-A	5.24 P.M.	9-A	10.48 P.M.	8-A	4.12 A.M.
11-A	.09 P.M.	20-A	.33	19-A	.57	18-A	.21
21-A	.18	30-A	.42	29-A	11.06	28-A	.30
31-A	.27	40-A	.51	39-A	.15	38-A	.39
41-A	.36	50-A	6.00	49-A	.24	48-A	.48
51-A	.45	60-A	.09	59-A	.33	58-A	.57
1-B	.54	10-B	.18	9-B	.42	8-B	5.06
11-B	1.03	20-B	.27	19-B	.51	18-B	.15
21-B	.12	30-B	.36	29-B	12.00 Md.	28-B	.24
31-B	.21	40-B	.45	39-B	.09 A.M.	38-B	.33
41-B	.30	50-B	.54	49-B	.18	48-B	.42
51-B	.39	60-B	7.03	59-B	.27	58-B	.51
4-A	1.48	3-A	7.12	2-A	12.36	1-A	6.00
14-A	.57	13-A	.21	12-A	.45	11-A	.09
24-A	2.06	23-A	.30	22-A	.54	21-A	.18
34-A	.15	33-A	.39	32-A	1.03	31-A	.27
44-A	.24	43-A	.48	42-A	.12	41-A	.36
54-A	.33	53-A	.57	52-A	.21	51-A	.45
4-B	.42	3-B	8.06	2-B	.30	1-B	.54
14-B	.51	13-B	.15	12-B	.39	11-B	7.03
24-B	3.00	23-B	.24	22-B	.48	21-B	.12
34-B	.09	33-B	.33	32-B	.57	31-B	.21
44-B	.18	43-B	.42	42-B	2.06	41-B	.30
54-B	.27	53-B	.51	52-B	.15	51-B	.39
7-A	3.36	6-A	9.00	5-A	.24	4-A	.48
17-A	.45	16-A	.09	15-A	.33	14-A	.57
27-A	.54	26-A	.18	25-A	.42	24-A	8.06
37-A	4.03	36-A	.27	35-A	.51	34-A	.15
47-A	.12	46-A	.36	45-A	3.00	44-A	.24
57-A	.21	56-A	.45	55-A	.09	54-A	.33
7-B	.30	6-B	.54	5-B	.18	etc.	
17-B	.39	16-B	10.03	15-B	.27		
27-B	.48	26-B	.12	25-B	.36		
37-B	.57	36-B	.21	35-B	.45		
47-B	5.06	46-B	.30	45-B	.54		
57-B	.15	56-B	.39	55-B	4.03		



45.—Diagram Illustrating Progress of Coking in Adjacent Ovens on a pushing schedule "by threes" (drawing by The Koppers Co.), with indication of temperature gradients in each oven.

a "series" of numbers in regular rotation, a "series" being all of the numbers ending in 1, all of those ending in 2, etc.

A commonly adopted schedule is one "skipping three series" at a time, from the 1's to the 4's, then to the 7's, 10's, etc. From the accompanying table (19) it will be seen that by this schedule, operating 120 ovens with one pusher, 35 ovens will be pushed, after No. 4 for instance, before returning to push its next neighbor No. 3, and 83 ovens will be pushed before returning to the other adjoining oven No. 5.

With 18-hour coking time and with one pusher serving two batteries of 60 ovens each, the *period* available *for pushing, charging* and *levelling* each oven is 9 minutes, $\frac{(18x60)}{(\ 120\ )}$. On shorter coking periods and with larger batteries this interval is shorter but in such case, if necessary, the various operations may be expedited by utilizing the time taken up in replacing and luting doors and charging with coal to move the machine back and level the charge in the next preceding oven.

Using the schedule shown above, on 18-hour coking time, it may be seen that when oven No. 11-A, for example, is pushed at 6.09 A.M., its next neighbor, 10-A, has been charged since 5.24 P.M., or 12 hours and 45 minutes, while the other adjoining oven (12-A) has been charged since 12.49 A.M., or 5 hours and 24 minutes. With 18-hour coking time, it is apparent, oven 10-A will have coked to a stage more than two-thirds of completion and oven 12-A hardly one-third complete, when 11-A is pushed. (See Figure 45 for a graphic representation of this condition.)

In this schedule, the age of the plus and minus ovens at the time of each pushing may be tabulated as follows:

TABLE 20.

PUSHING SCHEDULE BY "THREES."

No. of Series	Age of Plus Oven		Age of Minus Oven	
	In No. of Ovens Pushed	In Hours and Minutes	In No. of Ovens Pushed	In Hours and Minutes
1	36	5–24	85	12–45
4	36	5–24	84	12–36
7	36	5–24	84	12–36
10	35	5–15	84	12–36
3	36	5–24	84	12–36
6	36	5–24	84	12–36
9	36	5–24	84	12–36
2	36	5–24	84	12–36
5	36	5–24	84	12–36
8	36	5–24	84	12–36
1	36	5–24	85	12–45
4	36	5–24	84	12–36
7	36	5–24	84	12–36
etc.				

At each pushing it is evident one of the adjoining ovens is at an age more than double that of the other.

Other Possible Schedules. It is possible so to arrange the order of series of ovens by means of an irregular and somewhat complicated rotation that greater age and more nearly equal age in the adjoining ovens may be secured at each pushing. In the following schedule the sequence is so chosen that each series is one unit lower than the 4th series back:

TABLE 21.

SPECIAL SCHEDULE DEVISED TO SECURE MORE EVEN AGES IN ADJOINING OVENS.

Rotation of Series	Age of Plus Oven (in number of series of ovens pushed)	Age of Minus Oven (in number of series of ovens pushed)
1	4	6
8	3	6
3	5	6
5	4	6
10	4	6
7	4	6
2	4	6
4	4	5
9	4	7
6	4	6
1	4	6
8	3	6
3	5	6
etc.		

Another schedule of this kind, which has actually been in use at some plants, follows a somewhat different rotation:

TABLE 22.

Series Rotation	Age of Plus Oven (in number of series of ovens pushed)	Age of Minus Oven (in number of series of ovens pushed)
1	6	4
5	4	6
9	6	4
7	5	6
2	5	4
4	4	6
10	6	4
6	4	6
8	6	5
3	4	5
1	6	4
5	4	6

Marquard's Patented Pushing System. A system of pushing, patented[24] by W. B. Marquard, has been developed mathematically with the design of securing the maximum ages in "plus" and "minus" ovens, or the nearest to equality of ages that is practicable. This system is being used successfully at the large plant of the Carnegie Steel Co. at Clairton, Pa. It divides the total ovens into groups or cycles, each comprising an odd number of ovens, as eleven, or fifteen. At Clairton the pushing is on a "split-fifteen" schedule, this signifying that a series is made up of the like-numbered ovens in alternate groups of 15. The succession of series, as they follow one another, goes each time to the second back, as shown in Table 23 (page 159). The relative ages of ovens adjoining that pushed, it will be noted, differ quite regularly by only 12 or 13 pushings (that is, one series).

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[24] U. S. Pat. 1,323,711 (1919).

Coke Handling: On the "coke side" of the oven battery, or the side where the coke leaves the oven when pushed, a *coke guide* (see Figure 44), or frame, consisting of two parallel vertical grids of iron can be moved from oven to oven as each is opened for pushing, and guides the coke mass over the 6-or-7 foot concrete platform (or over the base plate of the guide) into the *quenching car.* The latter (illustrated in Figure 46) is a steel car, electrically driven, of capacity ample for holding the coke from one oven, its bottom being inclined downward from the oven side to the movable gridded gates on the other side. These movable gates are operated by air pressure control from the cab at one end of the car, allowing the coke (after quenching) to fall quickly onto a *coke wharf* (Figure 46), also inclined, where the coke cools. It is gradually allowed to slide therefrom through a rotary feed on the lower side to a travelling belt, which conveys it to screening station or crushing plant.

Quenching of Coke is done at a quenching station (Figure 47), located 50-100 feet from one end of the row of batteries. The red-hot coke in the car is hauled quickly to the station, where, from an overhead tank, through nozzles, a liberal spray of water quenches a car in 45-50 seconds, requiring thus about 6,000 gallons. The hot water may be recovered if desired and pumped back to the tank for use again, some plants having found economy in such practice. About 1/6 of the water evaporates. The car is drained one minute before dumping on the wharf. A small amount of fine coke is washed from the car during the quenching, and is recovered periodically from the sump-trough by a drag-scraper.

The quenching operation requires careful attention so as to limit the percentage of moisture retained by the screened coke to a maximum of 3.0 per cent., more than which is considered objectionable for metallurgical coke. Over-quenching also darkens the color, and dulls the appearance of the coke.

Coke Screening. From 5% to 10% of the total coke is "breeze" and dust screened from the run-of-oven coke by passing over stationary bar screens of ¾-inch to ⅞-inch openings, or through a rotary screen with round or square holes ⅞ inch to 1 inch in diameter. Considerable variation in practice as to screening and preparing coke necessarily

Example of Marquard's Patented Oven Pushing System—"Split Fifteen" Schedule Used at Clairton Plant of Carnegie Steel Co.

(192 ovens used as pushing unit, 16-hour coking time, 5 minutes each pushing.)

The ovens are divided into groups of 15, and a series comprises like-numbered ovens in each group, but the order of pushing skips one group each time, and goes back to the alternate groups after finishing thus the first half of a series. The succession between series is to the second back.

TABLE 23.

								Age of Plus Oven	Age of Minus Oven
								(Stated in number of ovens pushed, at 5 minutes each)	
No. 15 Series....	15	45	75	105	135	165		95	89
	30	60	90	120	150	180		101	89
No. 13 Series....	13	43	73	103	133	163		101	89
	28	58	88	118	148	178		101	88
No. 11 Series....	11	41	71	101	131	161	191	101	88
	26	56	86	116	146	176		101	88
No. 9 Series....	9	39	69	99	129	159	189	101	88
	24	54	84	114	144	174		101	88
No. 7 Series....	7	37	67	97	127	157	187	101	88
	22	52	82	112	142	172		101	88
No. 5 Series....	5	35	65	95	125	155	185	101	88
	20	50	80	110	140	170		101	88
No. 3 Series....	3	33	63	93	123	153	183	101	88
	18	48	78	108	138	168		101	88
No. 1 Series....	1	31	61	91	121	151	181	101	83
	16	46	76	106	136	166		101	96
No. 14 Series....	14	44	74	104	134	164		101	89
	29	59	89	119	149	179		101	89
No. 12 Series....	12	42	72	102	132	162	192	101	89
	27	57	87	117	147	177		102	89
No. 10 Series....	10	40	70	100	130	160	190	102	89
	25	55	85	115	145	175		102	89
No. 8 Series....	8	38	68	98	128	158	188	102	89
	23	53	83	113	143	173		102	89
No. 6 Series....	6	36	66	96	126	156	186	102	89
	21	51	81	111	141	171		102	89
No. 4 Series....	4	34	64	94	124	154	184	102	89
	19	49	79	109	139	169		102	89
No. 2 Series....	2	32	62	92	122	152	182	102	89
	17	47	77	107	137	167		102	89
No. 15 Series, etc.								95	89

follows the varied requirements of the coke market and the different outlets for its disposal. In the blast furnace field alone the question of size of coke and its influence on furnace results is one meeting wide divergence of opinion among experts. It is discussed more fully in another chapter. "Domestic" coke in various sizes may be and is at many plants prepared by crushing the run-of-oven coke and running it over graded rotary screens.

Coke "breeze" is now ordinarily used as boiler fuel on the plant, special chain-grate or other stokers having been adapted to its successful use, with the aid of blower-driven blast to increase the draft.

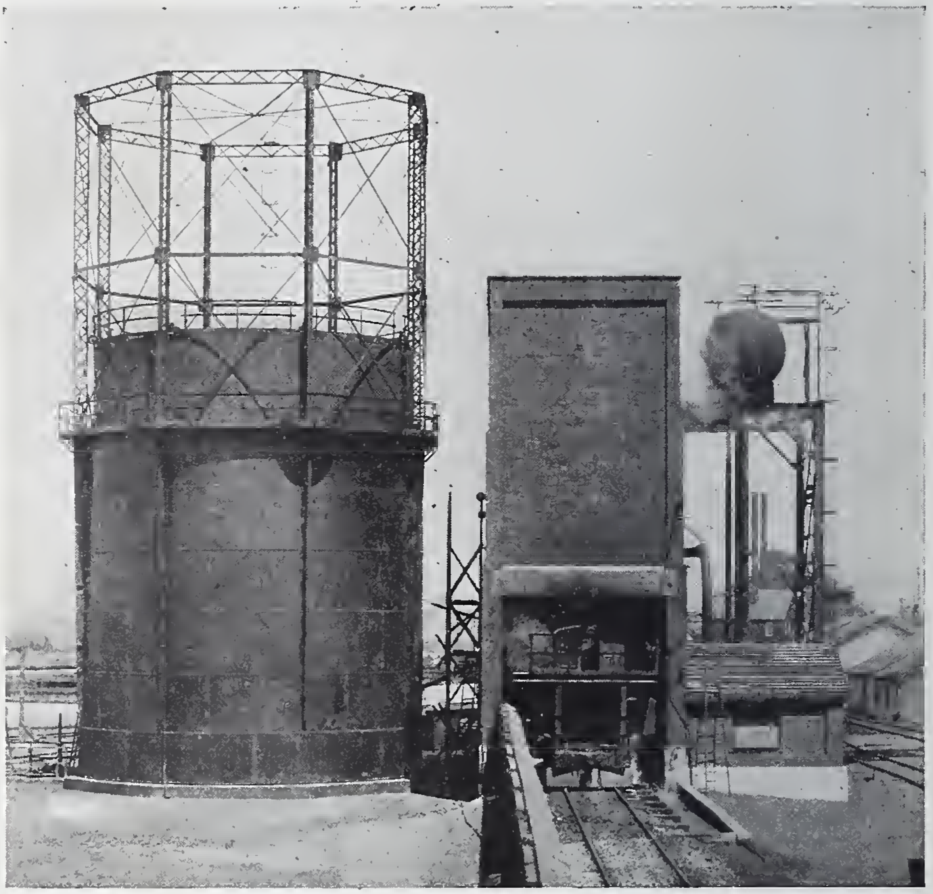

FIG. 47.—Coke Quenching Station.

The Yield of Total Coke exceeds that indicated in the laboratory by the established methods of coal analysis. That is to say, in the coke oven a materially greater yield of coke is obtained than corresponds to the sum of the percentages of fixed carbon and ash in the coal, together with the small additional amount of volatile matter usually contained in the oven coke. This excess of oven yield may with some coals amount to as much as 5 or 6 per cent. (based on the coal).[29]

[29] The following figures of actual operation averaged from daily and monthly records over a period of 12 months are furnished (in private communication)

The excess coke yield is due to the deposition of carbon by thermal decomposition of hydrocarbons in the gases and tar vapors as they pass through the highly heated coking mass. This discrepancy between laboratory and plant yields in coke, well illustrates the proximate nature of the so-called volatile matter in coal, and the fact that it is not a constituent of coal but the result of decomposition processes which may vary widely according to conditions such as temperature, mass of coal, rate of heating, etc.

Return of Fuel Gas to the Oven Flues. The ovens are heated in most cases (in present American practice), by combustion of a part of the gas evolved from the coal, after it has been cleaned, cooled and stripped of by-products. The use of producer-gas, however, or other externally produced fuel gas, for this purpose is increasing.

The cleaned oven-gas, under pressure of the exhauster, is passed, in requisite amount, into a holder, of the common telescopic-drum type, and of a size commensurate with the number of ovens to be served, usually 30,000 to 100,000 cubic feet. This holder acts as a constant-head reservoir, creating its own pressure on the supply lines to the oven-flue burners. The surplus of gas, not required for maintaining the proper head in the fuel-gas holder, is led through "boosters" (generally turbo-blowers electrically driven) which distribute the surplus gas under pressure to points of consumption outside the plant. A "bleeder," or emergency escape valve, is provided to allow burning of the surplus in the air when necessary. In some plants a fuel-gas holder is dispensed with, and constant gas pressure maintained by a governor.

Fuel gas pressure on the oven flue burners is controllable at the battery by regulators—and may be varied as between coke side and pusher side. The former, where the oven width is greater, is usually given a higher gas pressure. For regulating the temperature of the flues the gas pressure is varied. It may be anywhere between 20 mm. and 80 mm. of water. The distinction is important, however, between quantity of gas burned per unit of time (which largely affects the temperature), and pressure under which it is supplied to the burners (affecting the length and character of the flame). The quantity depends on the size of opening at the outlet, and the pressure behind it. Diaphragms with certain orifices are often placed in the gas supply

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by H. P. Zeller, formerly Superintendent of the by-product coke plant, Toledo Furnace Co., Toledo, O., now General Manager, Donner-Union Coke Co., Buffalo, N. Y.:

Coal mixture, 85 per cent. high-volatile (Elkhorn, Ky., and Eagle, W. Va.) and 15 per cent. low-volatile (Pocahontas, W. Va.)		
Average volatile matter in the coal mixture (dry basis).......	34.0	per cent.
Average volatile matter in the coke produced (dry basis).....	1.25	" "
Theoretical yield of coke (100 — 34.0) plus 1.25/.66...........	67.9	" "
Actual average yield of coke in ovens (dry coke to dry coal)..	73.3	" "
Excess above theoretical..	5.4	" "

lines to provide that pressure on the burners which is best suited to the conditions desired.

Gas cocks and the small gas supply lines to the flues must be kept clear and in free-working condition (Figure 48). If the gas be poorly cleaned in scrubbers and tar extractors, deposits occur in the pipes, valves and burners. The effect of this is noted in poor heating conditions and must be promptly cleared up by steaming out the lines. Occasionally for very hard deposits (formed of complex gums from

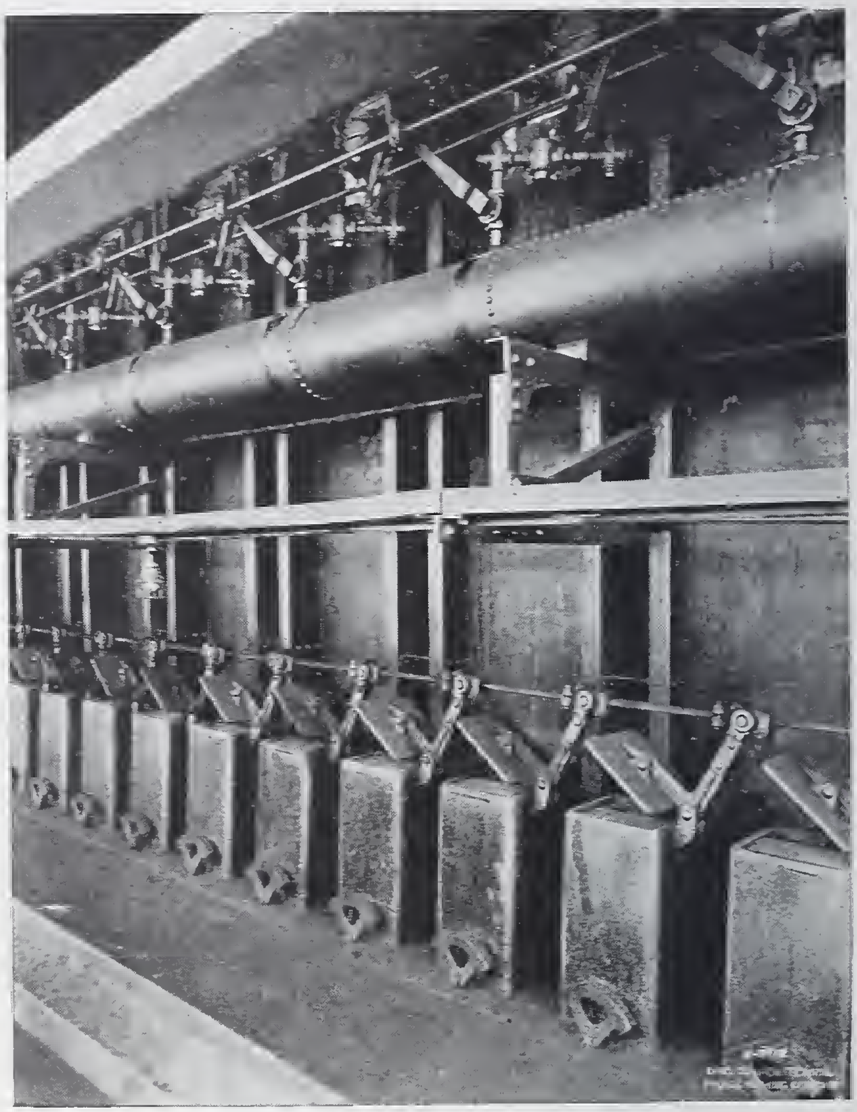
FIG. 48.—View of Fittings for Gas Supply and Air Supply to Koppers Ovens (under charging bench of oven battery).

the light oil, or of ammonia compounds) the use of solvents may be necessary.

In vertical-flued ovens (such as Koppers) where removable gas-nozzles at the base of the flues admit the fuel gas, carbon deposits often build up in the nozzles and must be burned out with air through the decarboning device (see page 184). In the use of this device especial care must be taken to admit air only when gas is shut off and not sooner than 5 minutes after shutting off the gas, since otherwise an explosion may easily occur and the nozzles be displaced or "dumped." Carboning is generally due to high heats at the nozzles and the presence of hydrocarbons or tars of easily decomposable nature in the gas. It may sometimes be caused by insufficient air.

Waste Gas Composition. The waste gas issuing from the flues to the regenerators or chimney-flue contains the water vapor (superheated steam) and carbon dioxide formed by combustion, the residual nitrogen of air and gas, and the oxygen remaining from excess air. The presence of carbon monoxide is rare, and when found indicates insufficient air or imperfect combustion due to other causes. An excess of air of 5 per cent. to 25 per cent. is commonly used. The content of oxygen (in the cool dry gas) runs ordinarily then between 1.0 and 4.0 per cent., and (when burning coke oven gas) the content of carbon dioxide 6.0 to 10.0 per cent., according to the amount of excess air.

General Statement on Coke-Oven Heating. Variation in Oven Design Therefor. In another chapter (Chapter 9) the various types of by-product coke oven are illustrated and described. Since the principal feature in which these types differ among themselves lies in the method of supplying heat to the oven walls and of recovering the heat of waste gases, the description of the various oven-heating systems is best deferred until the oven types have been described.

It may be said here in general, however, that for the heating of the ovens, gas is burned with preheated air in flues, either vertical or horizontal, forming a part of the wall structure on each side of the oven. Some types provide separate sets of flues for each wall of each oven, with a strengthening division wall between, while others make each row of flues itself a division wall supplying heat to two ovens and economizing thus in space and cost.

It is essential that the heat be so evenly distributed over that part of the oven wall with which coal is in contact that coking will progress evenly at all points and come to completion with practical uniformity over the entire length and height of the oven. On the other hand, a good oven should have provision for maintaining lesser heats in the tops, so as to minimize thermal decomposition of ammonia and other by-products.

Economy of heat is secured by using the sensible heat of the waste gases from the flues to regenerate (pre-heat) air for combustion by application of Siemens' regenerative principle, or of the recuperative principle, supplemented by "waste heat boilers" in case a demand for a large steam output exists. Since the heat applied in effecting carbonization is a direct loss and a heavy expense to be charged against the value of the products, that design of oven which most reduces this loss has a distinct advantage to weigh against others.

Control of Gas Pressure, Chimney Pull (Draft), and Air Supply: On page 254 (Chapter 10) this subject is treated in detail in connection with the discussion of the general subject of the heating of by-product coke ovens.

Refractory Materials of Oven Construction.

The choice of the refractory materials for oven walls, flues, regenerators, etc., is one of the most important factors in the success of a coke oven plant. Not only in life of the plant, and therefore rate of amortization of its cost, but in operating efficiency, rate of output, and cost of upkeep, are the refractories deeply concerned.

Silica brick almost exclusively now in America are used in walls, flues and regenerators of coke ovens. They are made from American raw material, and contain 96.0-98.0 per cent. SiO_2. In manufacture, the best grades of brick are carefully and thoroughly burned at temperatures reaching 1,300°-1,400° C. (2372°-2552° F.), so as to convert as large a proportion as possible of the quartz crystals into their allotropic forms, crystobalite or tridymite, or both. This conversion when complete causes a permanent expansion of the material amounting approximately to 20 per cent. in volume.[30]

Since, however, the conversion is never complete in commercial brick, even though twice-burned, they undergo further expansion in use, varying with the quality and method of manufacture of the brick. Such expansion must be allowed for by providing open joints at intervals when the brick are laid (see pages 275-6). According to the conditions of manufacture of the brick it may vary from 0.12 inch to 0.20 inch per linear foot, so that a coke oven wall 38 feet long expands 4 inches to 7 inches in length during heating up.[31] In practice the amount of space usually left in the expansion joints is ¼ inch to ⅜ inch per linear foot.

This expansion of silica brick occurs chiefly in heating up to 2,000° F., that is, there is little if any important degree of expansion by changes in temperature above that point, a feature very favorable in their practical use.

When silica brick are too rapidly heated in manufacture or in use, minute cracks develop, due to the sudden and uneven conversion of the quartz crystals. This results in "spalling" or the chipping off of pieces during use.

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[30] A. B. Searle, "Refractories and Their Use," London, 1917, pp. 236-8.

[31] A. H. Middleton, "Silica Brick for Coke Ovens," *Colliery Guardian*, **122**, 1203 and 1273 (1921) and Trans. Ceramic Soc. (England), **22**, (1922-3), 168-81; see also F. W. Sperr, Jr., in "American Fuels," Bacon and Hamor (1922), p. 161, who states that the expansion of silica brick is about ⅜ inch per linear foot.

The refractoriness of silica brick or resistance to softening by heat, when not under load, is scarcely, if at all, higher than that of the best grades of clay brick. When under load, however, they retain their rigidity much better in the higher ranges of temperature, collapsing quickly when the melting point is reached. In coke oven practice with silica brick it is not safe to carry the flue temperatures above 1,500° C. (2,732° F.). Ovens are not infrequently operated, however, in America at 2,550°-2,600° F. in the flues.[32]

Quartzite brick and **Clay brick** are used for coke oven construction in England and European countries more than any other kind. They were formerly used also in some of the older plants in America, now largely rebuilt with silica linings. The former (quartzite) is a mixture, natural or artificial, of clay and ganister or quartz, containing usually from 70 to 77 per cent. SiO_2. These brick, on account of their gradual distortion under load at high temperatures, cannot be heated with safety above 1,200° C. (2,192° F.). Clay brick contract slightly on heating up; quartzite undergoes slight expansion, varying with composition.

At the by-product coke plant of the Illinois Steel Co., at Joliet, Illinois, 280 Koppers regenerative ovens, were built in 1908—in four batteries, each battery of 70 ovens being constructed of different refractory material. One battery was built of American silica brick, one of American quartzite, and two of imported (German) quartzite, all built within the year. A valuable comparison was thus afforded of these different brick in service, although the matter was complicated by considerable differences in the kind of service to which the different batteries were subjected, as to regularity of operation, especially. The No. 1 battery, of American silica brick, appeared to give better service, both in the matter of replacements and in rate of output. The entire plant was rebuilt early in 1922, above the oven floors, with silica brick. It is necessary, in drawing a fair conclusion from the results at this plant, to give due weight to the fact of the damaging effect of an expanding coal mixture used at times, and to the fact that two batteries (quartzite brick) were cooled down and reheated during a period of depression in 1914-15.

Refractory cement for the laying of silica brick is ordinarily a mixture of finely ground ganister rock (silica) and ground "bats" (1 to 1) with 15-25 per cent. clay, the latter being added merely for securing the necessary plasticity. The percentage of Al_2O_3 by analysis should not exceed 6.0 per cent. The brick are closely laid so that the cemented joints are thin. The cement must have as nearly as possible the same degree of refractoriness and qualities of expansion by heat as the brick themselves.[33]

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[32] See Chap. 10, "The Heating of By-Product Ovens," pp. 250-1, for additional data on the heat transmitting properties of silica brick.

Corrosion of Coke Oven Walls. The gases evolved from some coals contain hydrochloric acid or compounds thereof, which, on clay brick, exert an important corroding action (see p. 129). On silica brick this action is slight. The slagging action, however, of basic mineral matter of the coal, such as lime, magnesia or soda, on the silica surface of the brick is in some cases serious.

Plant Layout.

The ground plan, or arrangement of units in the by-product coke plant, is generally called the "layout," and varies according to local requirements and conditions. A detailed plan of an existing plant, drawn to scale, and showing the various working units, spaced and sized essentially as built and operated, is given in Figure 176 (in Appendix). It is to be noted in connection with this particular layout, that it does not provide the average amount of coal storage and coke storage space usually considered advisable (although this requirement depends greatly on conditions). The primary coolers in this plant, also, are not placed, as now is more customary, *outside* of the by-product building.

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[33] R. J. Montgomery, "Silica Cement," Amer. Soc. for Testing Materials, Proceedings, Vol. 18 (1918), Pt. II, p. 351.

Chapter 9.

Various Types of By-Product Coke Ovens.

Introductory. Only those types of coke oven which are in use in the United States of America are described in this chapter. A list of other types is appended, with references to descriptive articles thereon, to be found elsewhere.[1]

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[1] *List of By-Product Coke Oven Types:*

(* Described herein.)
(A, B, C, D, E,—see references below for description.)

Horizontal flued:					
* Semet-Solvay					
Huessener	(A)	(B)	(C)		
Simon Carves	(A)	(B)	(C)		
* Rothberg					
Vertical flued:					
Coppee	(A)	(B)	(C)		(E)
Otto	(A)	(B)	(C)	(D)	(E)
* Otto-Hoffman					
Otto-Hilgenstock					(E)
* Schniewind					
* Koppers					
* Wilputte					
Collin			(C)	(D)	(E)
Still			(C)	(D)	(E)
* Piette					
* Foundation					
* Gas Machinery Co.					
* Piron					
Simplex			(C)	(D)	
B. C. O. (British Coke Ovens, Ltd.)			(C)	(D)	
Flueless:					
* Roberts					

(A) John Fulton, "Coke," International Textbook Co., Scranton, Pa., 1905.
(B) T. H. Byrom and J. E. Christopher, "Modern Coking Practice," Crosby, Lockwood & Son (London), 1910.
(C) G. Stanley Cooper, "By-Product Coking," Benn Bros., Ltd. (London), 1916; 2nd Ed. 1922.
(D) W. A. Ward, "Modern By-Product Coke Oven Construction" (Summary, illustrated), *Journal of the Society of Chemical Industry,* **39**, 198-211T (1920).
(E) C. A. Meissner, "The Modern By-Product Coke Oven," a paper presented to American Iron and Steel Institute, May 23, 1913; printed as U. S. Senate Document No. 145, 63rd Congress, 1st Session (1913).

The historical development of the by-product oven, having been excellently presented by other authors [2] is omitted here on the ground that it helps the reader very little in understanding the modern survivals among oven types, and may even confuse him by a multiplicity of detail in description of design and operation.

Essential Differences in Types. Although possibly in the future, by-product coke oven types may be distinguished by characteristic shape and method of operating, as between vertical, horizontal and inclined ovens, at present undoubtedly the essential difference lies in the method of heating the oven chamber.

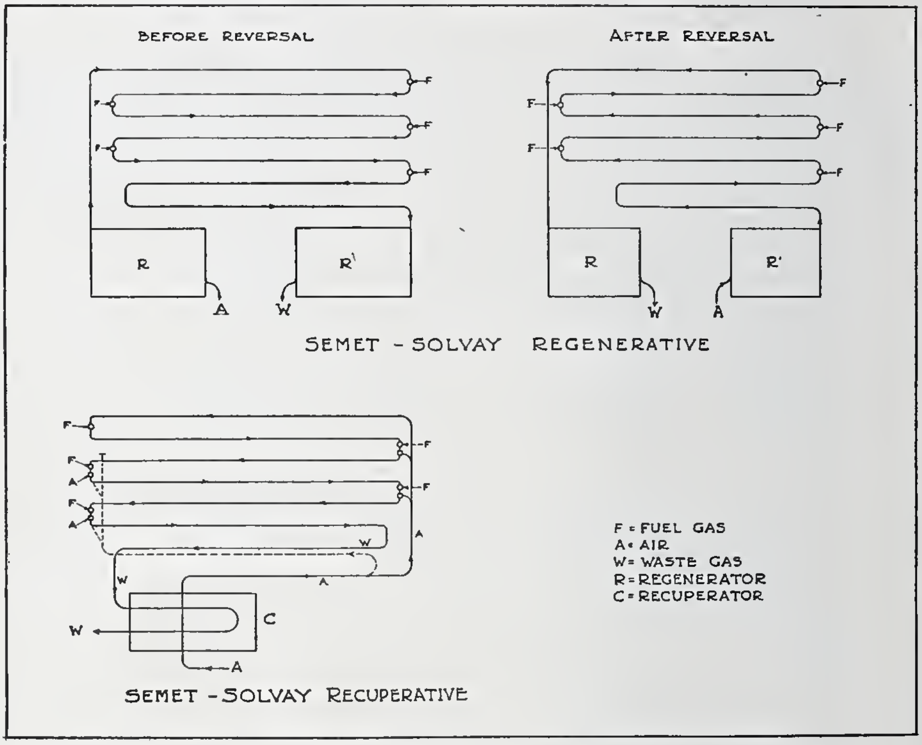

Fig. 49.—Diagram of the Heating System of Semet-Solvay By-Product Coke Ovens.

In general, the size and shape of the various by-product coke ovens, and their method of operation (as to charging, discharging and recovery of gas and by-products) are essentially the same in all types. In yields and quality of products there is also no material difference. The wall temperatures do not vary characteristically with the oven type, but the degree of uniformity of temperature in the oven has much to do with the type, and the system of heating used.

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[2] Byrom and Christopher, "Modern Coking Practice," Crosby, Lockwood & Son (London), 1910; G. Stanley Cooper, "By-Product Coking," Benn Bros., Ltd. (London), 1916 (2nd Ed. 1922); John Fulton, "Coke," International Textbook Co., Scranton, Pa., 1905.

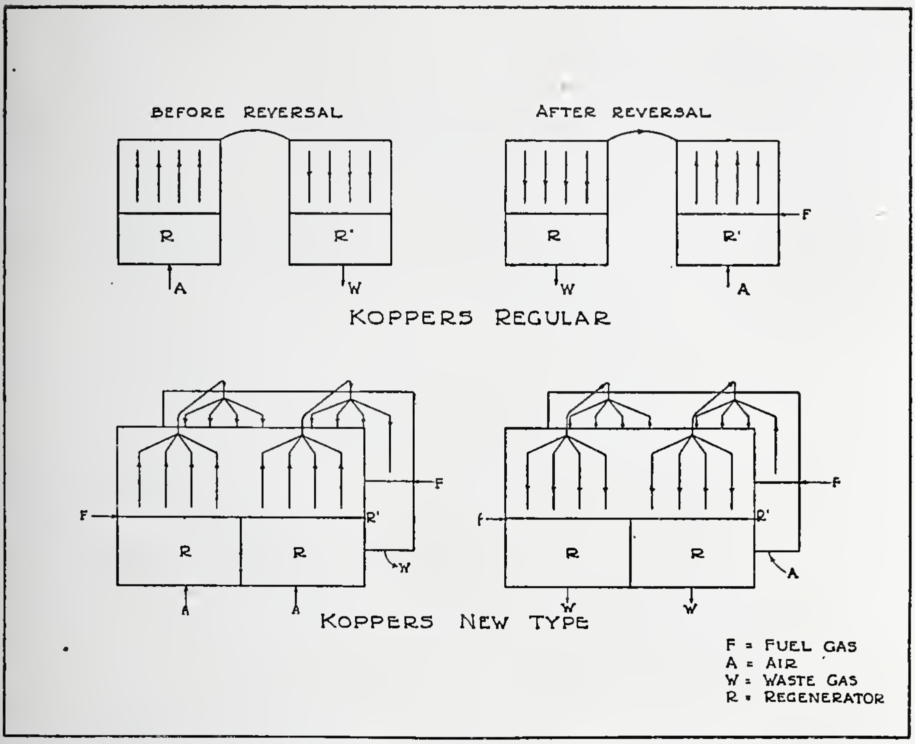

FIG. 50.—Diagram of the Heating System of Koppers By-Product Coke Ovens.

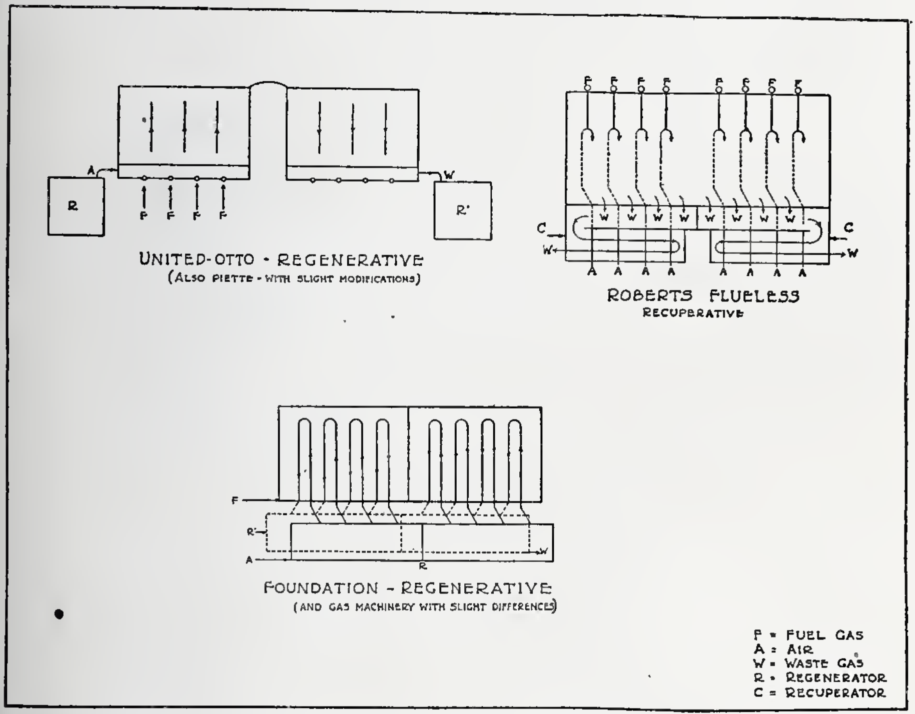
R
R'
A
W
F
UNITED-OTTO - REGENERATIVE
(ALSO PIETTE - WITH SLIGHT MODIFICATIONS)
C
ROBERTS FLUELESS
RECUPERATIVE
FOUNDATION - REGENERATIVE
(AND GAS MACHINERY WITH SLIGHT DIFFERENCES)
F = FUEL GAS
A = AIR
W = WASTE GAS
R = REGENERATOR
C = RECUPERATOR

FIG. 51.—Diagram of the Heating Systems of United-Otto, Roberts, and Foundation By-Product Coke Ovens.

Types of by-product ovens differ mainly in the arrangement of their heating flues, whether vertically or horizontally, in the method of applying the Siemens' regenerative principle to preheating the air for combustion, and in the method of introducing gas and air to the flues.

A comparison, merely diagrammatic, of the flow of gases in the heating systems of various types of by-product coke ovens is shown in Figures 49, 50, and 51.

The types of oven used in America include:

A. *Horizontal-flued ovens:*
   1. Semet-Solvay, regenerative, recuperative, or waste heat; sole-flue, type.
   2. Rothberg. (American plants now in disuse.)

B. *Vertical-flued ovens:*
   1. Koppers—cross regenerative—called herein "Koppers, Regular" (with individual single regenerators, and with reversal of the heating gases from end to end of the row of flues).
      Koppers, special "New Type," regenerative, in which a cross-over flue over the top of the oven, permits reversal of the heating gases from side to side, instead of end to end.
   2. Wilputte—modification of the Koppers type.[3]
   3. Otto-Hoffman and Otto-Schniewind.
   4. "Foundation"—of the Foundation Oven Corporation.
   5. Piette—of the Belgian-American Coke Oven Corporation.
   6. Roberts (a so-called "flueless" type, in which no distinct continuous flues appear, but in which the gas and air are introduced vertically, downward).
   7. Gas Machinery Co.
   8. Piron.
   9. Klönne.

The Semet-Solvay By-Product Coke Oven.

The Semet-Solvay oven is the only horizontal-flued type which has actively survived to the present time. In America, it was the pioneer in the by-product coking industry. The first ovens of the recovery type in this country were the 12 Semet-Solvay built in 1893 by The Solvay Process Co. at Syracuse, N. Y. (See Figures 2 and 3.)

With this type of oven, much was done in developing the art of by-product coking in this country, and toward overcoming the strong prejudices rife among coke users and investors of capital in the early days of the industry. Technically coke oven operation, especially in the recovery of by-products, was in this early period put on a firm foundation of efficiency by Semet-Solvay practice.

The Semet-Solvay oven is characterized by two distinctive features: (1) It is heated by flames burning horizontally and serially instead of vertically and in parallel as in the majority of oven types; (2) a battery of these ovens is so constructed that each oven is structurally independent of the ones next adjoining. Each oven has its own individual heating flues, separated from those of the next adjoining oven by a

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[3] Adjudged an infringement of Koppers, by U. S. Circuit Court of Appeals, Philadelphia, May 22, 1919.

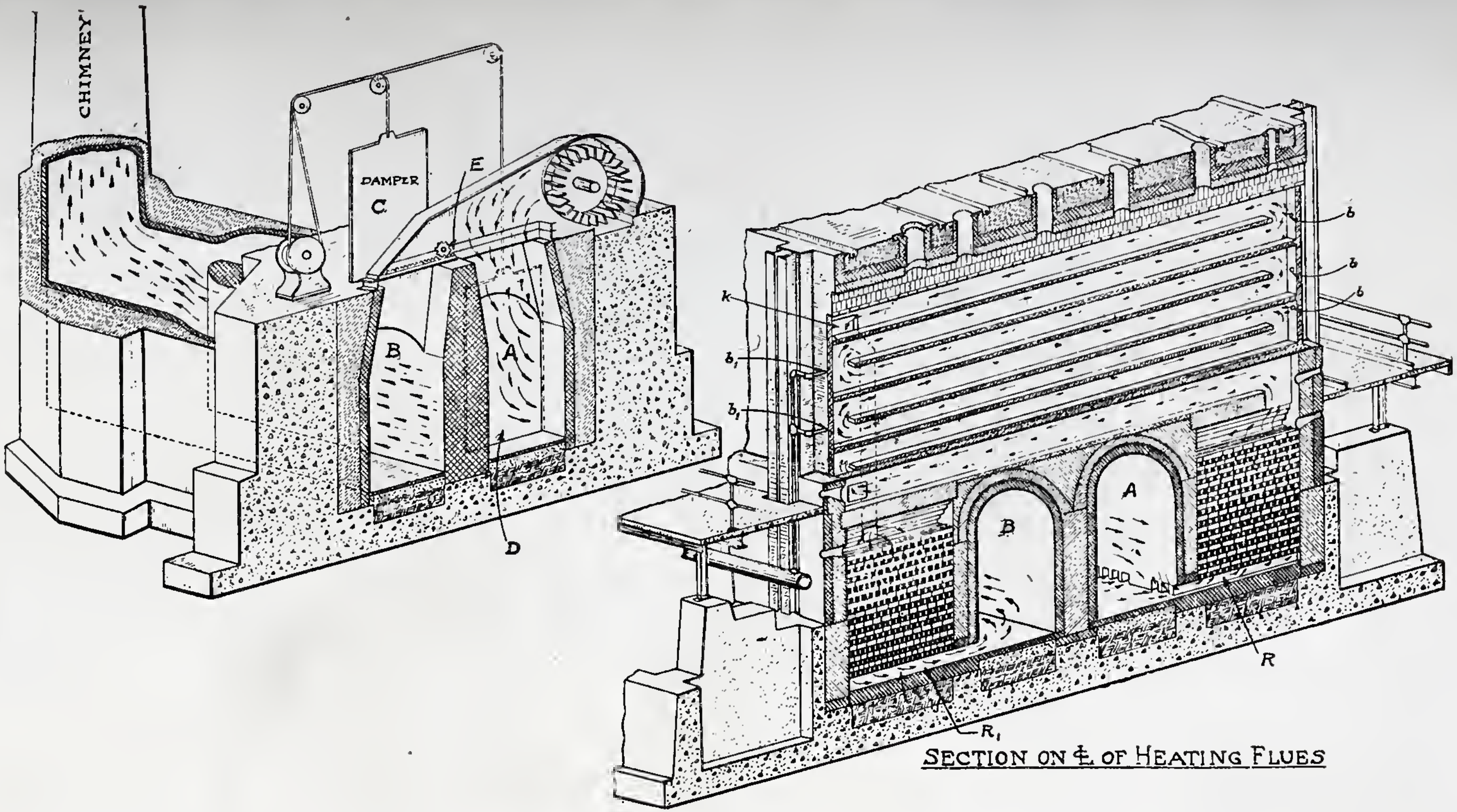

Fig. 52.—Standard Regenerative Semet-Solvay By-Product Coke Oven, Perspective of Vertical Section through Flues.

solid wall of fire brick, which lends additional strength to the battery structure and acts as a heat-retaining reservoir. Individual regenerators under each oven are provided when regenerative heating is used.

The Semet-Solvay method, used in its regenerative oven, of admitting at one point all of the air necessary for combustion, and admitting gas in successive portions at intervals along the course of travel through the heating wall, is a feature essentially characteristic of this type.

The Semet-Solvay Regenerative Oven.

Figure 52 shows in perspective the standard Semet-Solvay regenerative oven, longitudinally in vertical section through the flues. The oven chamber varies much in size, but in recent installations has been 36 feet long, 11 feet high and 19½ inches in average width, tapering generally 2 inches from end to end. The flues in the modern oven are six on each side and there is one sole flue directly beneath the oven. The flues are constructed of silica shapes laid in the manner shown in Figure 54. From the interior of heating flue to interior of oven the brick is 4 inches in thickness. Three gas burners on the coke discharge side and two on the pusher side enter the ends of the flues from riser pipes outside the

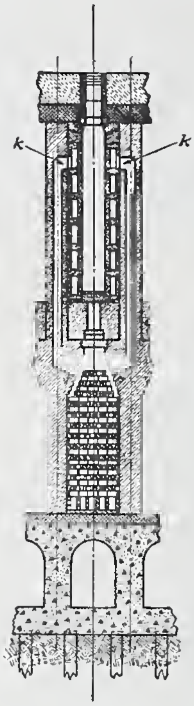

Fig. 53.—Standard Regenerative Semet-Solvay By-Product Coke Oven, Transverse Section.

battery. They are thus easily accessible to regulation in alternate flues. The top flue, which is designed to be kept cooler, is not provided with a gas burner. Four charging holes admit the coal from the larry on top of the battery, and the gas offtake pipe rises from the oven top 5 feet distant from the pusher end.

A solid division wall, 18 inches thick, separates the flues of one oven from those of the next, continuing downward between the regenerators to the concrete mat supporting the battery. In this division wall at the pusher end are two vertical flues for the passage of preheated air *from* the regenerator, or, after periodic reversal, the counter-passage of hot waste gases *to* the regenerator (k, k, Figure 53). One of these flues leads to the oven on the left and the other to the oven on the right.

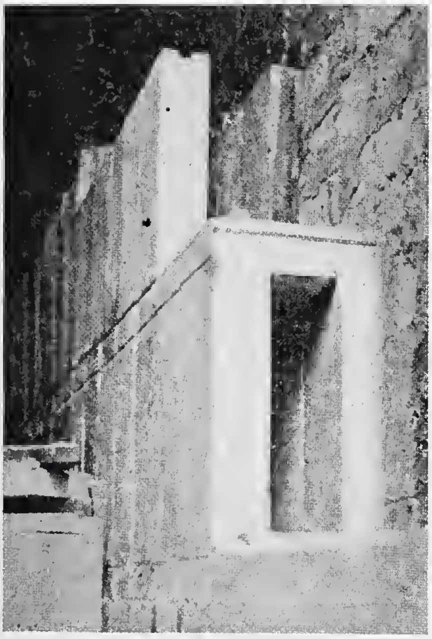

Fig. 54.—Manner of Laying Flue Tile in Wall of Semet-Solvay By-Product Coke Oven.

Two regenerators underlie each oven, being individual to the oven and lying in position parallel to its long axis, one at each end. They are separated by two central transverse flues running the length of the battery carrying cold air blown by a fan to the regenerators on one side, or waste gases to the stack from the regenerators on the other side. The regenerators are approximately 11 feet high by 4 feet wide and 7½ feet long, filled with silica brick in checquer formation to within 18 inches of the top (Figure 55). The openings to the bottoms of the regenerators from the chimney flue are so graduated in size as to give proper regulation of draft in accordance with the relative

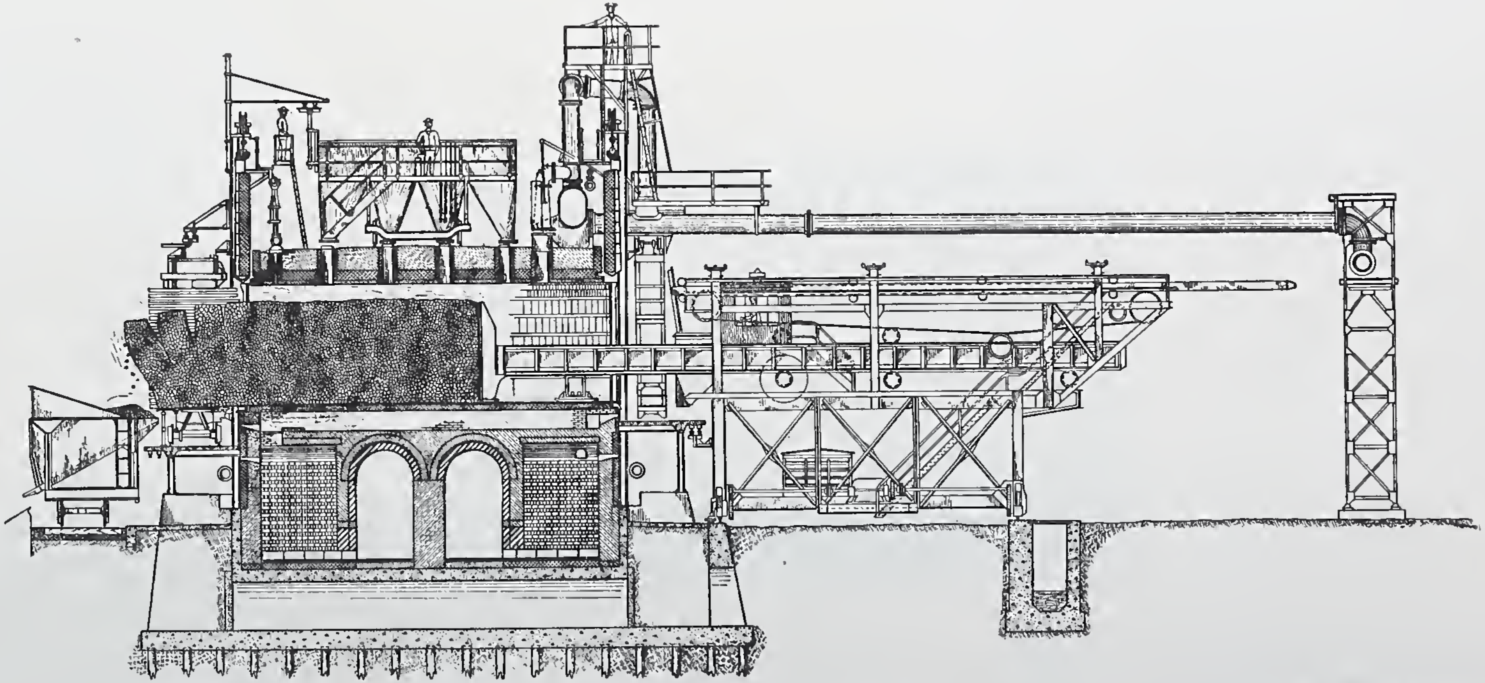

FIG. 55.—Longitudinal Section through Oven, Semet-Solvay Regenerative By-Product Coke Oven, Showing Pusher Machine, Coal Larry and Coke Car.

distance from the chimney. A sliding damper also over the opening from the top of the regenerator to the sole flue may be used for individual regulation.

In the *Semet-Solvay system of regeneration,* reversal is made only of air and waste gases. The fuel gas burns continuously at all burners.

As indicated by arrows in the illustration (Figure 52), during one period (½ hour), cold air from the blower[4] passes along the large central duct (A), where it is warmed somewhat, enters the regenerator (R) which has been heated during the previous period by waste gases, absorbs heat from the checquers, passes upward into the sole flue, traverses same to its opposite end and issues thence through side ports into the lowest of the flues flanking the oven on either side. Using only the heat of the regenerator and that stored in the brickwork, the air traverses the sole flue and the first of the side wall flues before meeting gas for combustion. At the beginning of each succeeding flue more gas is introduced.

The waste products of combustion pass along the top flue, thence through lateral ports into the downtake flues in the division walls, and from these to the regenerator (R) where they give up a large part of their sensible heat to the checquers. The central duct (B) connected to the chimney pulls the waste gases from the regenerators to the stack.

At the end of the ½ hour period, reversal is made by closing communication from duct B to the chimney and simultaneously opening duct A to the chimney by means of the dampers C and D respectively (Figure 52). The air current, also simultaneously with the reversal of draft, is reversed from duct A to duct B by means of the sliding damper E. These reversing dampers are located at one end of the battery of ovens and operate on the battery as a whole, there being no individual damper to be changed at each oven. The reversal is made automatically by motors electrically controlled by clock mechanism.

After this reversal, for ½ hour, air enters through duct B and regenerator R, passing upwards through the vertical flues in the division walls, and takes a downward passage through the flues in the heating wall instead of upward as in the preceding period. At the last of the period, when the regenerator has become reduced in temperature by the incoming air, there is a tendency toward cooling of the top heating flues of the oven, a desirable condition, but on reversal the hot waste gases from the lower flues raise the top flue again to a temperature somewhat above the maximum of the regenerator. Control of the top flue temperature is secured by regulation of the top gas burner.

The Semet-Solvay system of regeneration has the advantage of simplicity, requiring no periodic alteration in burning of gas or of individual dampers at each oven. It avoids also the objectionable periodicity, end-to-end, pertaining to regenerative heating of vertical-flued ovens wherein the reversal is from the half at one end to the half at the other, and each half is heated in alternate periods under somewhat fluctuating conditions, differing in the two halves.

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[4] A blower is not always necessary and sometimes is not used.

On the other hand, the Semet-Solvay system offers difficulties in securing, by regenerative means, the preheating of gas, which is necessary for efficiency when producer gas or blast furnace gas is used instead of coke oven gas. Other means of preheating the gas may, however, be substituted; blue water gas also may be used in the oven flues without preheating.

The system promotes thorough mixing of air and gases in the flues by their long travel and the turns from flue to flue. The introduction of all of the air at one point, reinforced at successive points by burning gas, makes for the long flames necessary in this type of oven and for the even heating of the oven through convection and conduction of the heat carried in the very rapid current of gases.[5]

Inequalities of heating due to fluctuations inherent in the regenerative process are, fortunately, as in all regenerative heating, periodically balanced through the reversals, since in each period the points of maximum temperatures are the minima of the preceding period, and vice versa. The volume of gases passing per second, and their velocity, is, in the Semet-Solvay regenerative oven, much greater in the bottom flue during one period, and in the top flue during the next period.

The Semet-Solvay oven, from an engineering point of view, has a notable element of strength in the central supporting arches under the battery, longitudinal to it but transverse to the individual oven. It is also given substantial character by the heavy division walls between ovens, although this feature together with that of individual heating flues for each oven increases the ground area required for a given number of ovens, by an amount approximating 35-40 per cent., over other types. A further advantage of the independent character of each oven afforded by the division walls and the separate sets of flues, lies in the accessibility of each oven to repairs independently of adjoining ovens.

To provide for uniform coking of the wide and narrow ends of the tapered oven, the Semet-Solvay system has recourse to the burning of gas at a higher rate at the coke side burners.

Semet-Solvay Recuperator Oven.

In the recuperative system of preheating the air, there is no periodic reversal of flow of air and waste gases. The air is preheated by passing continuously through narrow gas-tight ducts of fire brick construction interlaid between passages conducting the hot waste gases in counter direction.

The Semet-Solvay recuperator oven is illustrated in Figure 56. The air, already somewhat warmed under the battery, passes upward through the narrow vertical passages of the recuperator (individual to each oven) and into a sub-sole flue (a) paralleling the oven axis. At the end of this flue the preheated air turns to one side, ascends a vertical duct in the division wall and thence issues through lateral ports (n, n) into the heating flues. Or it may pass in part to the other end of the oven along horizontal flues paralleling the main sole flue and on a level with it, thus, at the other end rising in the division wall, similarly, to the air ports of that end. The vertical air flues have ports in either direction.

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[5] See further on this subject, Chapter 10, pp. 252-3; also, W. H. Blauvelt, Bulletin American Institute of Mining Engineers, 1912, p. 1309 ff., and discussion, *ibid.*, 1913, pp. 155-165.

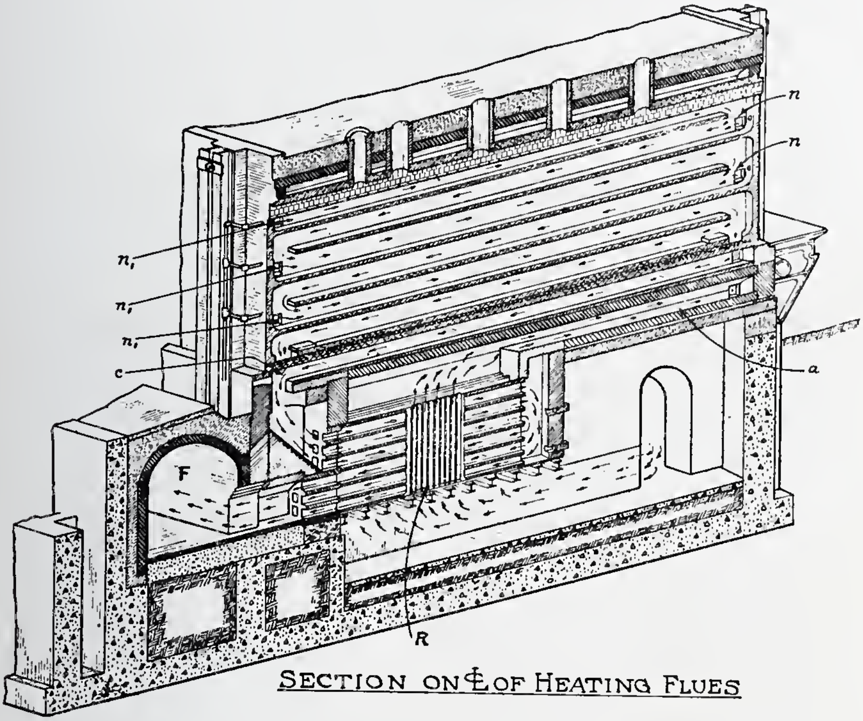

Fig. 56.—Standard Recuperative Semet-Solvay By-Product Coke Oven, Perspective of Vertical Section through the Flues.

The flow of air and burning gas in the heating flues is thus continuous from the top to the bottom flue, and on reaching the latter the waste gas divides, one portion traversing the bottom heating flue and the other the sole flue, where it preheats the air entering alongside. Both portions of waste gas unite at (c) and enter the top tiers of horizontal passages in the recuperator, returning through the bottom tiers and thence to the chimney flue (F). In the majority of Semet-Solvay recuperator installations in this country, the waste gases (at a temperature of 1,250°-1,300° F.) pass through boilers or economizers after leaving the recuperator, and thus permit utilization of a large part of the sensible heat not recovered in the recuperator.

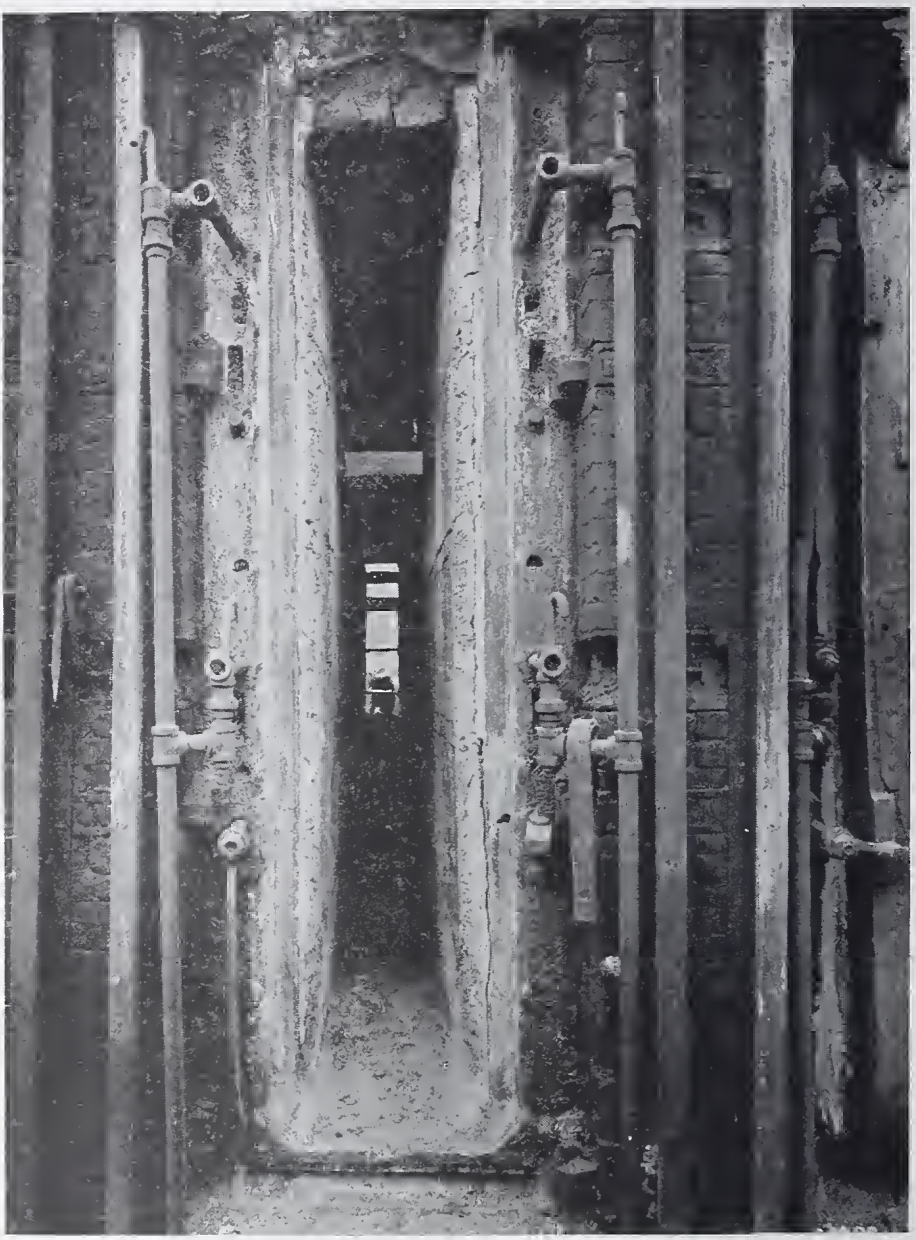

Fig. 58.—View Through Semet-Solvay By-Product Coke Oven, End to End, after 16 Years' Service.

There are various designs of recuperator which have been adapted to coke oven use, some of which have parallel flues with counter-current flow of waste gas and air, some having flues at right angles, as in the type shown (Figure 56), and others differently disposed, the object being in all, however, to transfer the maximum amount of heat of the waste gases and avoid leakage from waste gas to air flues.

The recuperator type (as also the waste heat type described below) has the advantage of simplicity in operation and construction, as compared to the regenerator oven, but has been found less economical in returns from the total heat of the gas burned. This question is discussed fully in later paragraphs.

The Semet-Solvay Waste Heat or Cold Air Oven.

The earlier Semet-Solvay ovens installed in this country were of the simple waste heat type. A late model, six flues high, of this oven is shown in Figure 57. The sole flue acts in some measure as a recuperator, further than which, however, there is no means of preheating the air for combustion. The waste gases accordingly carry away from the oven a large amount of heat (their temperature being 1,500°-1,650° F.) which is ordinarily absorbed in great measure in waste heat boilers. The oven furnishes a comparatively small amount of surplus gas, and does not lend itself readily to high-speed operation, but in many cases it proves suitable and has given good service where excess steam generating capacity and not surplus gas is a desideratum.

The air, somewhat warmed, enters from the large duct (c) (Figure 57) under the battery to a sub-sole flue (d) under each oven, and thence to the main sole flue (e). It may then rise by the ascending air flues at that end and enter the heating flues by the lateral ports (m_1, m_2 and m_3), or pass along the sole flue (e) on both sides of the hot central waste gas passage until it is drawn upwards to the air ports (m_4, m_5, and m_6) at that end of the heating flues. The direction of flow of flame and waste gases is continuously downward to the sole flue (central duct therein), and thence through the chimney flue (F) to the boilers. Air admission at the lateral ports near the gas burners is regulated by sliding dampers. There are ports in both directions from the vertical air duct.

For decreasing the gas velocity and necessary draft differential in the lower flues, two pairs of the lower flues may be operated in parallel (by patent of W. H. Blauvelt, U. S. 947,525). When large ovens are operated at high capacities the volume of burning gases would otherwise become very large.

The Koppers Cross-Regenerative Oven "Regular" Type.

The most widely used vertical-flued oven in America is the Koppers, originated in Germany, but introduced into America in 1907, and since that time modified and improved materially by the American builders. All of the Koppers ovens in America are of the regenerative type, and have individual regenerators end to end, parallel with the longitudinal

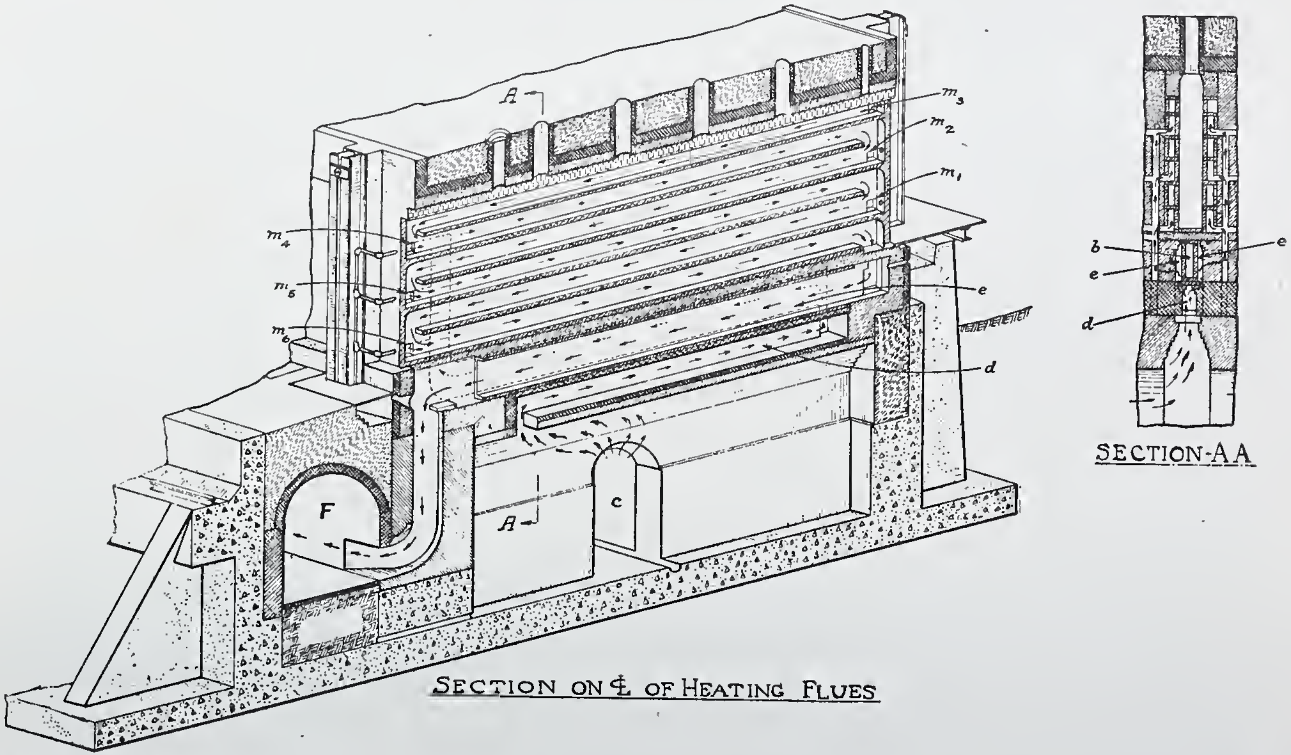

FIG. 57.—Standard Waste-Heat Semet-Solvay By-Product Coke Oven, Perspective of Vertical Section through the Flues.

axis of each oven. The reversal of air and waste gas flow at the end of each period (½ hour) is from end to end of the oven, that is, from half of the row of flues in the wall to those of the other half. This system necessarily makes for some periodicity in heat conditions in the oven end for end, although in well designed ovens with good regeneration such periodicity is small.

In a late type of the Koppers' regenerative oven, used in a number of the new installations (see pages 194-201) the reversal of flow is not end-to-end but side to side, i.e., from the flues on one side of an oven to those on the other through cross-over ducts in the brickwork above the oven. This feature has the effect of eliminating the irregularities of temperature, end-to-end, caused by the usual system of reversing, and it secures in other ways still more important advantages in heating conditions, explained in later paragraphs.

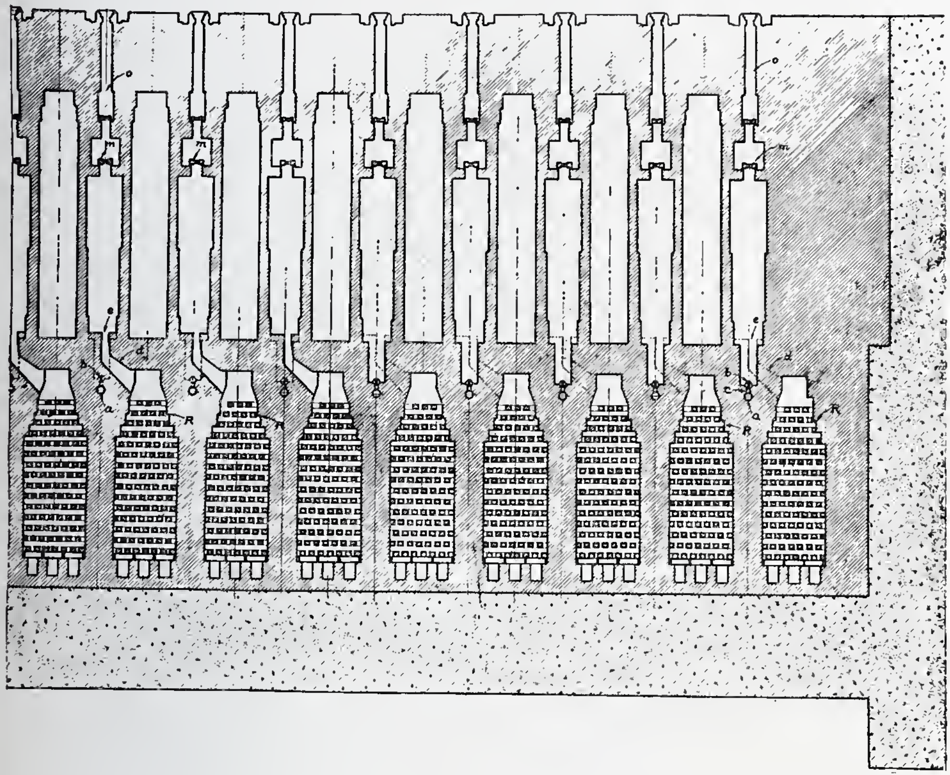

Fig. 59.—Koppers Cross-Regenerative By-Product Coke Ovens, Transverse Section.

As distinguishing features of the Koppers oven, there stand out (1) individual control of heating conditions in each flue through separate means of adjustment of fuel gas, air supply and draft, and (2) individual regenerators paralleling each oven, and introducing hot air directly at the base of each individual heating flue.

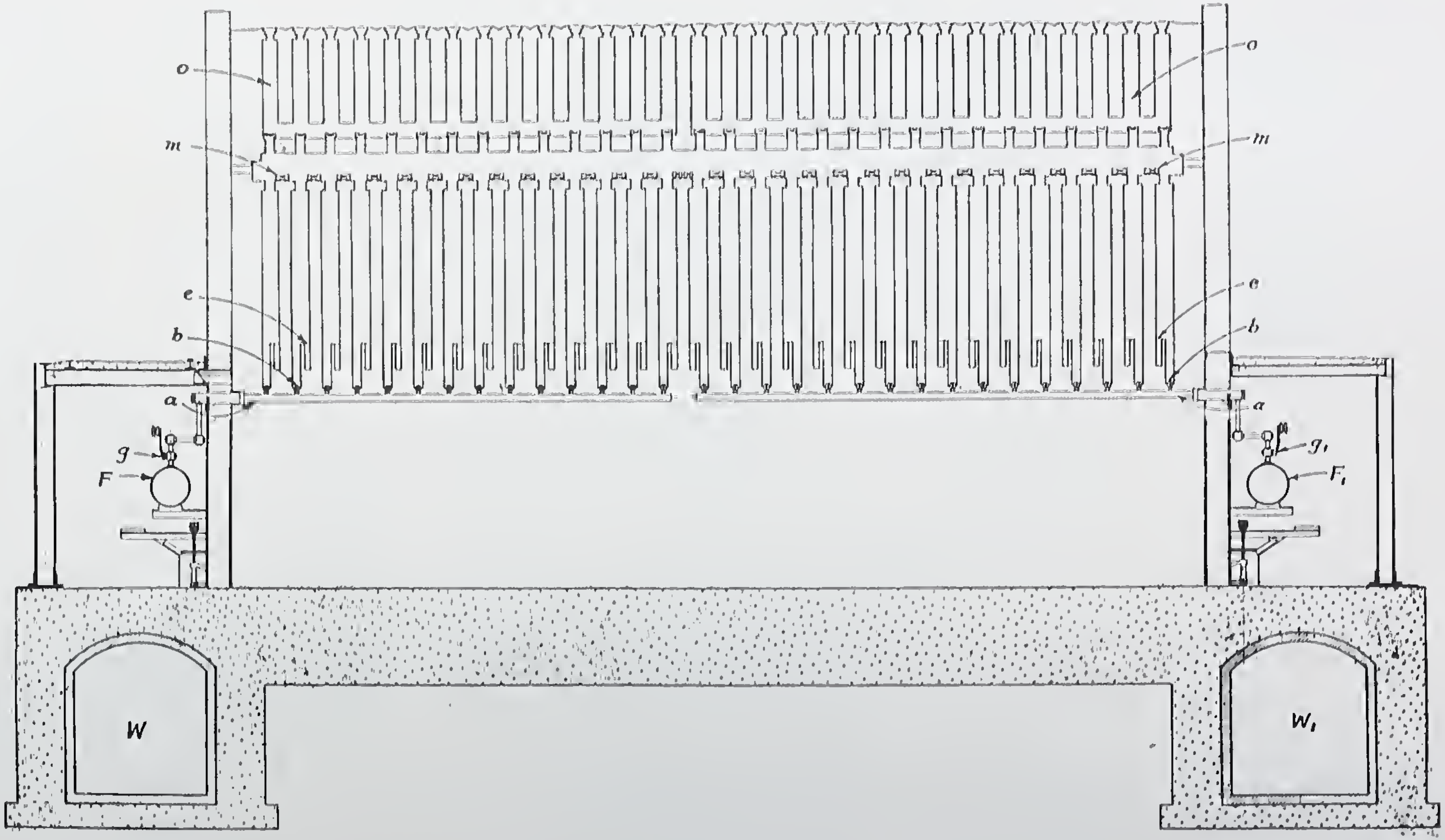

Fig. 60.—Koppers Cross Regenerative By-Product Coke Oven, "Regular" Type, Longitudinal Section through the Flues.

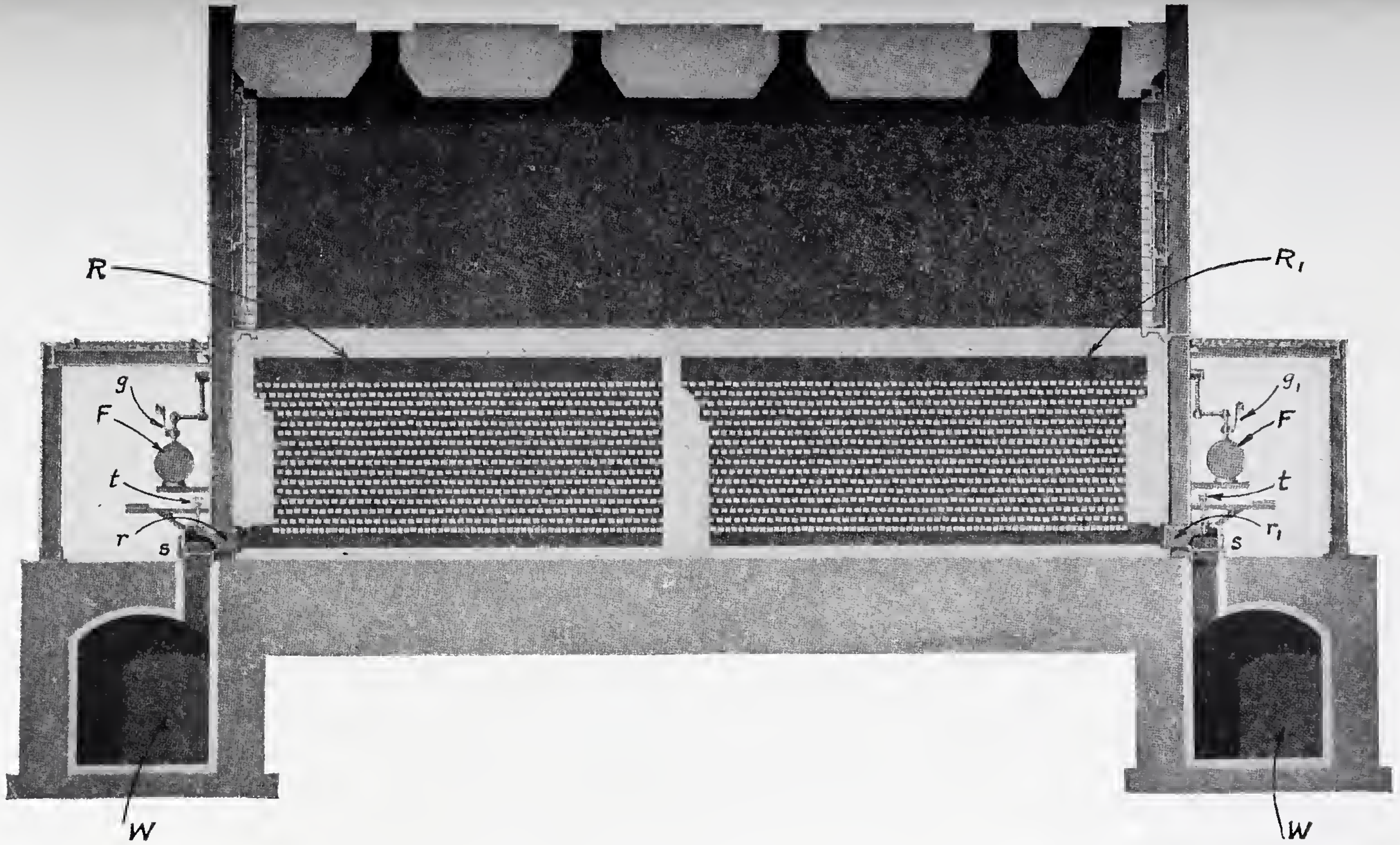

Fig. 61.—Koppers Cross Regenerative By-Product Coke Oven, "Regular" Type, Longitudinal Section through Oven.

The Koppers "regular," or "old type," oven is shown in Figure 59 in vertical cross-section, and in Figures 60 and 61 in longitudinal sections through the flues and through the oven, respectively. Although varying in dimensions in different installations, being in the latest, longer, higher and narrower, the average Koppers oven may be said to be 37 feet long, 10 feet high and 17 inches in average width (tapering 2 inches from end to end). There are 30 rectangular vertical flues on either side of each oven, each row (except the end ones in the battery) supplying heat to two ovens, adjacent on either side. A late type, not used at many installations, has triangular flues, 44 instead of 30, in each heating wall, half of them facing to one side and half to the other, thereby affording greater direct heating surface per unit of wall area and an increase in strength of the wall (see pages 192-4 and Figure 66). In some of the recent Koppers installations, a vertical taper is used in the oven chamber, amounting to two inches in all, but made in three steps, the oven being 2 inches narrower at top than at bottom.

Fuel gas is burned in one-half of the row of flues upward, and the flames unite in the common horizontal flue above, whence they pass downward through the flues in the other half of the wall. At the end of each regenerating period, the direction of flow is reversed.

A fuel gas duct (a) (Figure 60) passes under each row of flues transmitting gas to the base of each through a vertical duct (c), and a removable fire-clay nozzle (b) (Figure 59). Preheated air from the regenerator (R) enters the flue through the inclined duct (d), individual to each flue, and the air port (e) alongside the gas inlet in the base of the flue. In Figure 62 is shown a horizontal section of the base of rectangular flues. The size and position of the air ports (e and e′) are features of the design which have had to be worked out with great care, since they have much to do with the character of the flame and efficiency of heating. The air ports may be varied in size from flue to flue by the use of removable plugs to reduce the opening.

The gas nozzles are placed designedly at some distance (about 21 inches) below the point of air inlet, in order that they may escape such temperatures as would cause excessive "carboning," i.e., decomposition of the hydrocarbons in the gas. A certain amount of carboning, in spite of this, occurs, to counteract which a decarbonizing device is provided, consisting of a valve, or cock, at the outer end of each gas duct (a), controlled by the reversing mechanism, so as to admit air automatically and at definite intervals to burn off the hot carbon in the nozzles. Another device for this purpose recently patented[6] provides for directing the down-flowing hot waste gases, during one period, in part through the gas inlet nozzles on that side. The gas duct (a) is divided near the middle of its length; 14 flues at the coke discharge end of the oven burning gas at one time, and 16 flues at the pusher end taking the down-flow together, until after reversal the 16 flues at the pusher end burn the gas and the 14 at the coke end take the down-flow. The object of this unequal division is to give more intensive combustion per flue at the wider end of the oven, where there is more coal to be

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[6] J. Van Ackeren, U. S. Pat. 1,410,783, Mar. 28, 1922.

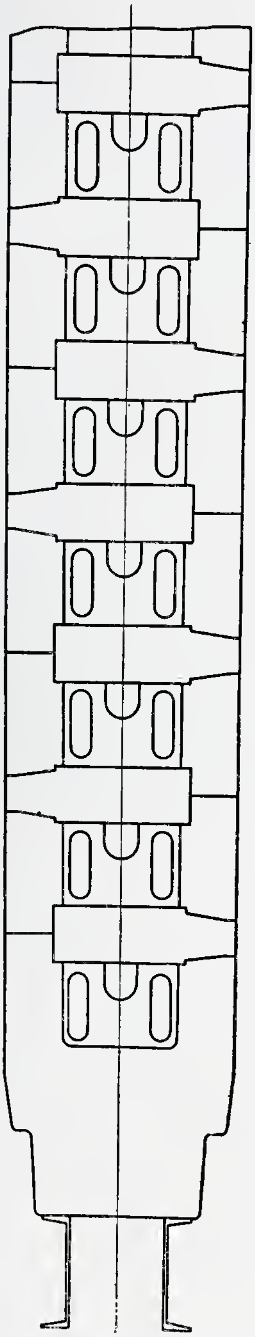

FIG. 62.—Drawing of the Base of the Flues, in part of a Koppers Oven Wall (showing gas inlets, in center of each flue, and air ports on either side).

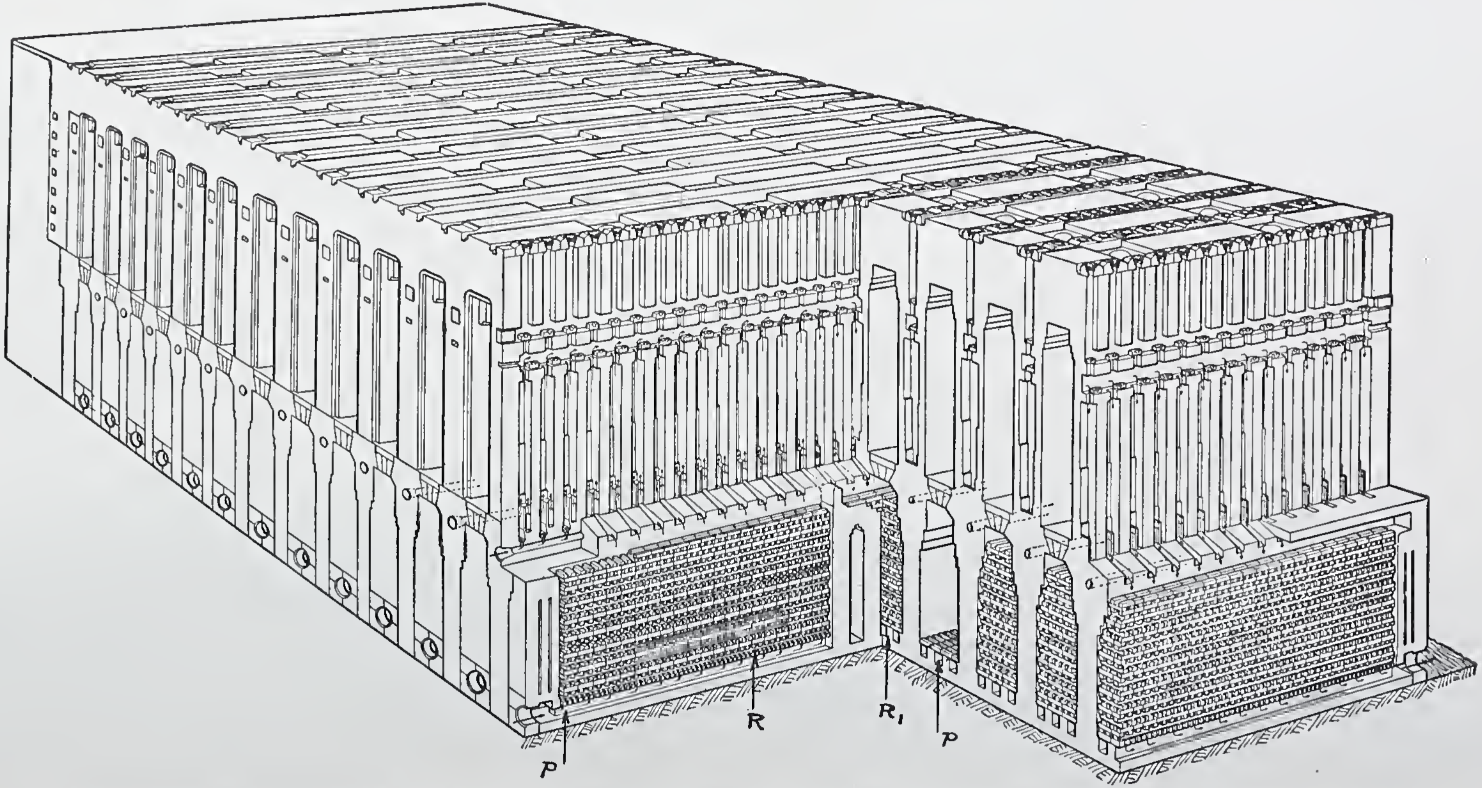

FIG. 63.—Perspective View of Battery, Koppers Cross Regenerative By-Product Coke Ovens, "Regular" Type.

coked. Control of draft is effected individually for each flue by the sliding bricks (m, m, Figure 60) over the openings into the horizontal flue. These dampers, as also the gas nozzles, are reached for regulation or removal from the top of the battery through "access flues" (o, o), one over each heating flue.

Gas nozzles and draft dampers are varied in size of opening, as their respective distances vary from the end of the oven. The horizontal flue may be considered as a duct closed at one end and having a series of openings in its lower side. The velocity of gases above these openings increases from end to center. According to Jos. Van Ackeren's exposition of "Heat Distribution in the New Type Koppers Coke Oven" [7] there is an increasing static pressure along this horizontal flue from its axis to its closed end, due to the decreasing gas velocity therein, the effect of which is governed by a mathematical constant (Figure 64). Assuming equality of suction at the base of the flues, gas will flow downward therefore in increasing measure from axis to outer end of the row of flues, and openings to the flues at their tops should be graduated accordingly, to be larger toward the center. Where, however, the flow is upward the varying static pressure over the flues acts with counter effect, the lower pressure (nearer the center) tend-

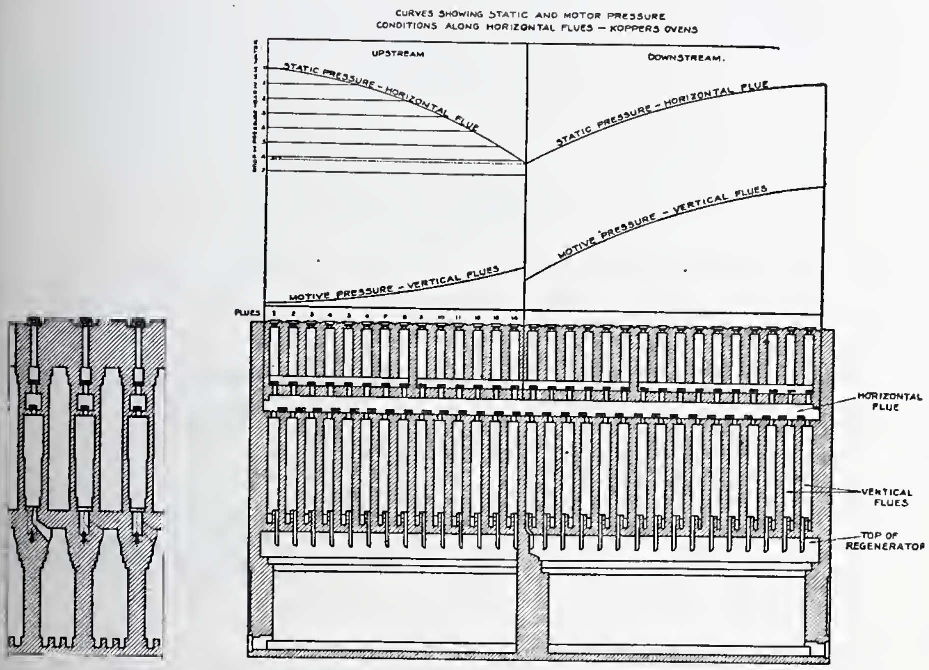
CURVES SHOWING STATIC AND MOTOR PRESSURE
CONDITIONS ALONG HORIZONTAL FLUES — KOPPERS OVENS
UPSTREAM
DOWNSTREAM.
STATIC PRESSURE - HORIZONTAL FLUE
STATIC PRESSURE - HORIZONTAL FLUE
MOTIVE PRESSURE - VERTICAL FLUES
MOTIVE PRESSURE - VERTICAL FLUES
FLUES
1
2
3
4
5
6
7
8
9
10
11
12
13
14
HORIZONTAL FLUE
VERTICAL FLUES
TOP OF REGENERATOR

FIG. 64.—Diagram Showing Variation in Static and Motive Pressures along Horizontal Flue, in Koppers "Regular" Oven (Up-stream on Left, Down-stream on Right). Diagram by Joseph Van Ackeren.

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[7] Transactions Amer. Inst. Mining and Metallurgical Engineers, March, 1923.

ing to increase the flow through the vertical flues in that section, so that the openings there should be smaller.

This opposite effect of the sliding brick settings on the up and down sides is often urged as a defect in the Koppers heating system, and so, in a measure, it may be regarded, since it tends undoubtedly to build up on one side in alternate periods some gradation in heat from center to end. But in actual practice this proves to be small. The sliding brick are given the proper settings for the up-draft side (smaller open-

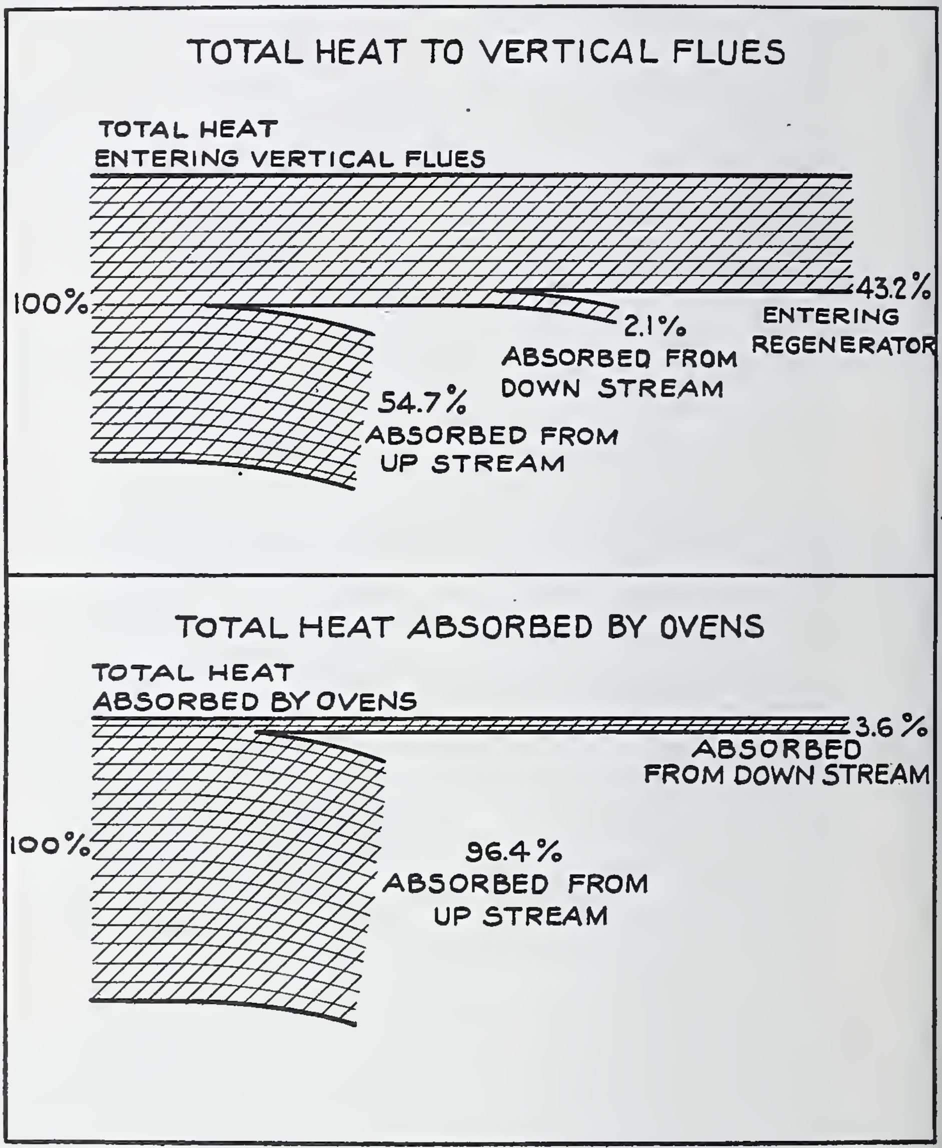

Fig. 65.—Diagrams Showing Relative Heat Absorption from Up-Stream and Down-Stream in Koppers Heating Wall. Diagram by Joseph V. Ackeren.

ings toward the center), and since much the greater portion of the heat transfer to the oven (96 per cent. according to Van Ackeren, *loc. cit.*) (see Figure 65) takes place on that side, the irregularity on the down draft side affects only a small heat transfer and is not serious.

In the New Type Koppers Oven, to be later described (pp. 194-201), this irregularity is still further minimized.

The gas nozzles admitting fuel gas to the flues are also graded in size of opening, being somewhat larger toward the inner end of the duct, owing to expansion of the gas by heat, and an increasing resistance due to friction.

The settings of nozzles and of sliding brick dampers in use on the Koppers ovens of the Carnegie Steel Co. at Clairton, Pa., for 19-hour coking time, have been reported by F. F. Marquard[8] as follows:

TABLE 24.

The following are Clairton Average Settings and Readings on 19-Hour Coking Time.

Gas pressure on pushing side	40 mm. of water
Gas pressure on coke side	50 mm. of water
Stack draft on pusher side	21 mm. of water
Stack draft on coke side	22 mm. of water
Temperature of waste gas at base of stack	275° C.
Gas burned per hour, pusher side	180,000 cubic feet
Gas burned per hour, coke side	200,000 cubic feet
Back pressure in collecting mains	2.5 mm. of water
Average draft at top of regenerator chamber—pusher side	.36 inch water (9.1 mm.)
Average draft at top of regenerator chamber—coke side	.40 inch water (10.2 mm.)
Opening in air inlet to regenerators—pusher side	59.7 square inches
Opening in air inlet to regenerators—coke side	84.7 square inches

NOZZLE BRICK SETTINGS.

Flue	1—coke side (end flue)	.49	square inch or	316.05	square mm.
“	2 to 12 inclusive—coke side	.35	“ “ “	225.70	“ “
“	13 and 14—coke side	.38	“ “ “	245.10	“ “
“	1—pusher side (end flue)	.35	“ “ “	225.7	“ “
“	2 to 12 inclusive—pusher side	.35	“ “ “	225.7	“ “
“	13 to 16 “ “ “	.38	“ “ “	245.1	“ “

SLIDING BRICK SETTINGS.

Flue No. 1	Coke side (end flue)	Full open	17.721	square inches
“ “ 2, 3, 4	“ “	60 mm.	8.103	“ “
“ “ 5, 6, 7	“ “	55 mm.	7.256	“ “
“ “ 8, 9, 10, 11, 12	“ “	50 mm.	5.874	“ “
“ “ 13, 14	“ “	45 mm.	5.119	“ “

[8] "The By-Product Coke Plant at Clairton, Pa.," a paper presented to American Iron and Steel Institute, May 23, 1919; Yearbook Amer. Iron and Steel Institute, 1919.

TABLE 24—*Continued.*

SLIDING BRICK SETTINGS—*Continued.*

Flue No. 1	Pusher side (end flue)	Full open	17.721	square inches
" " 2, 3, 4, 5	" "	60 mm.	8.103	" "
" " 6, 7, 8	" "	55 mm.	7.256	" "
" " 9, 10, 11, 12	" "	53 mm.	6.615	" "
" " 13	" "	50 mm.	5.874	" "
" " 14, 15, 16	" "	45 mm.	5.119	" "

The regenerators (R-R_1) whose arrangement may be seen most clearly by reference to the perspective sectional view of a battery in Figure 63, lie directly under the ovens, in position parallel to them. Under each oven is a pair of regenerators, placed end-to-end, each approximately 10 feet high by 17 feet long, and 2¾ feet wide. In the bottoms of the regenerators are passages (p p) for the entering air underneath the checquers, the checquer brick being laid designedly with graduated spacing, more open toward the inner end so as to distribute the air evenly, in the regenerator, end-to-end, overcoming in some measure the variable flow resistance therein. The Koppers regenerator, however, does not direct the flow of air in channels or in a divided course, but is designed, by the spacing and staggering of the checquer brick, to distribute it uniformly to the different flues.

At (r-r_1) (Figure 61) is the opening for admission of cold air from outside of the battery or for the exit of waste gas to the chimney flue (W). This passage is opened or closed to the air or to waste gas flue by means of the damper (s s). These various dampers on all of the ovens of a battery are attached rigidly to the rod (t) from the reversing mechanism. The fuel gas mains (for coke oven gas) are shown at (F, F) (Figure 61), along both sides of the battery, under the benches, with individual cocks (g g), in the riser pipes to each row of flues, these cocks being also connected to a rod from the reversing mechanism.

The reversal, at the end of each period (generally ½ hour) proceeds as follows: On the half hour, a clock-work mechanism automatically operates motors, at the end of the battery, which perform in succession the following steps: (1) Shut off the gas from (say) side (F) of the battery; (2) close the air inlets at (r) with simultaneous opening of the chimney flue dampers on that side; (3) open the air ports on the other side (F_1) shutting simultaneously the flue dampers, and finally (4) turn on the gas cocks on that side (F_1). The effect of this is to reverse the current of the flames in the heating flues of the entire battery; also, in regenerators R, to displace an upward flow of air by a downward flow of hot waste gases, or the reverse in regenerators R_1.

A certain interval of time must be allowed between the steps of reversal in order to permit any accumulated explosive mixture to be cleared from flues or regenerators.

Damaging explosions in flues, mains, etc., have been caused by neglect in observing the right order in gas and air reversals, or in allowance of time intervals.

In the Koppers battery, each wall between regenerators is directly beneath a flue wall and lends it firm support. The flue walls themselves supported thus, carry the weight of the superstructure and the coal-charging larries. The oven floors rest upon arches, designed for strength, forming the tops of the regenerator structures, and are supported also by the center wall longitudinal to the battery dividing the regenerators end-for-end.

As may be seen from the transverse section (Figure 59), the Koppers heating flue is wider at top than at bottom. In other words, the dividing wall between flue and oven decreases in thickness by steps from the bottom to the top of the heating flue, being 4 inches in the portion of minimum thickness. This feature tends to promote uniform heating of the oven through compensating for the higher heat at the base of the flues where combustion is at its highest rate and where heat is gained by radiation from regenerators and lower brickwork. It adds strength also to the oven walls.

An element of weakness in the Koppers heating wall is the horizontal flue, a continuous open space in the structure throughout its entire length. This flue, furthermore, in the prevailing or "old" Koppers type, must be comparatively large in section so as to carry *all* of the gases from the entire row of heating flues. In the later improved type, with "side-to-side" reversal (see pp. 195-6) this defect is in some degree remedied. There is in the old type a tendency to overheating of the center of the oven at the top, occasioned by the building up of the heat from the several vertical flues in the horizontal flue toward its center. This is, however, modified materially by the correspondingly increased velocity of hot gases at this point.

Points of regulation in the Koppers system of oven-heating are many. They comprise:

(1) those individual to each flue, viz., the gas nozzle at the base, and the sliding-brick draft control at the top;

(2) those individual to each oven, viz., gas cock in riser pipe to each row of flues, air inlet to regenerator (the area of opening being variable by "finger bars"), and draft outlet from regenerator, which may be dampered;

(3) those affecting the battery as a whole, the fuel gas pressure on the line from the holder, the amount of draft in the chimney flues on either side of the battery regulable by separate dampers, and the draft in the main stack flue.

Non-uniformity in heating of the oven wall, or as between individual ovens, may thus, at these many points, be controlled effectively, although the regulation affects less readily any vertical irregularities in wall temperature than it does the longitudinal. In other words, hot or cold spots along the oven wall, end-to-end, may be controlled more easily than a variation from bottom to top of the oven, the latter condition, however, being subject to control in the original design of the oven and flues.

The gas nozzles, the air ports to flues, and the sliding-brick flue dampers, are, in most cases, set according to known requirements before the beginning of operation, and for a given coking time and kind of coal do not ordinarily require further adjustment. Such adjustment, however, is possible, if needed, without interruption of the oven operation.

The Koppers Triangular-Flued Oven.

The triangular-flued oven, to which reference has already been made, is an improved Koppers type of recent origin. It is in use at a few plants and was at one time recommended by the American builders in preference to the rectangular-flued. Its main advantage lies in increased strength of the oven wall, resisting the bending stress from the pushing of coke. This type embodies no essential change other than that within the wall of heating flues.

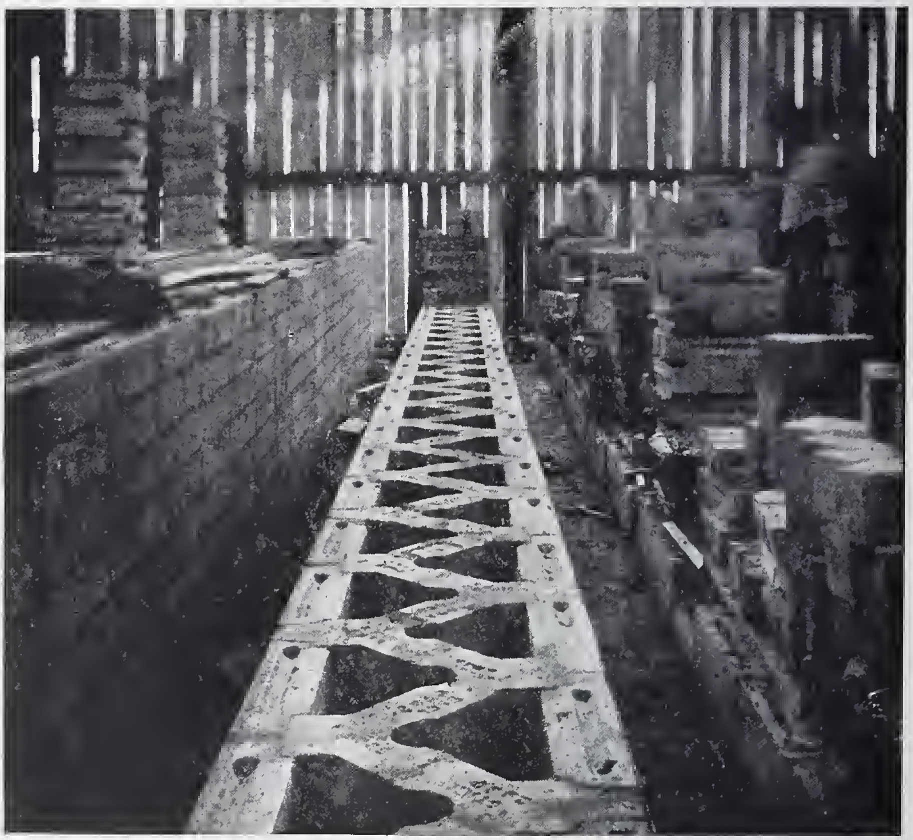

Fig. 66.—Heating Wall of Koppers Triangular-Flued Oven.

As shown in Figure 66, the wall structure is made up of two rows of flues of triangular cross section, overlapped and fitting closely, so that each row, although transmitting its heat primarily to one oven only, supplements in some degree the other row in heat transfer.

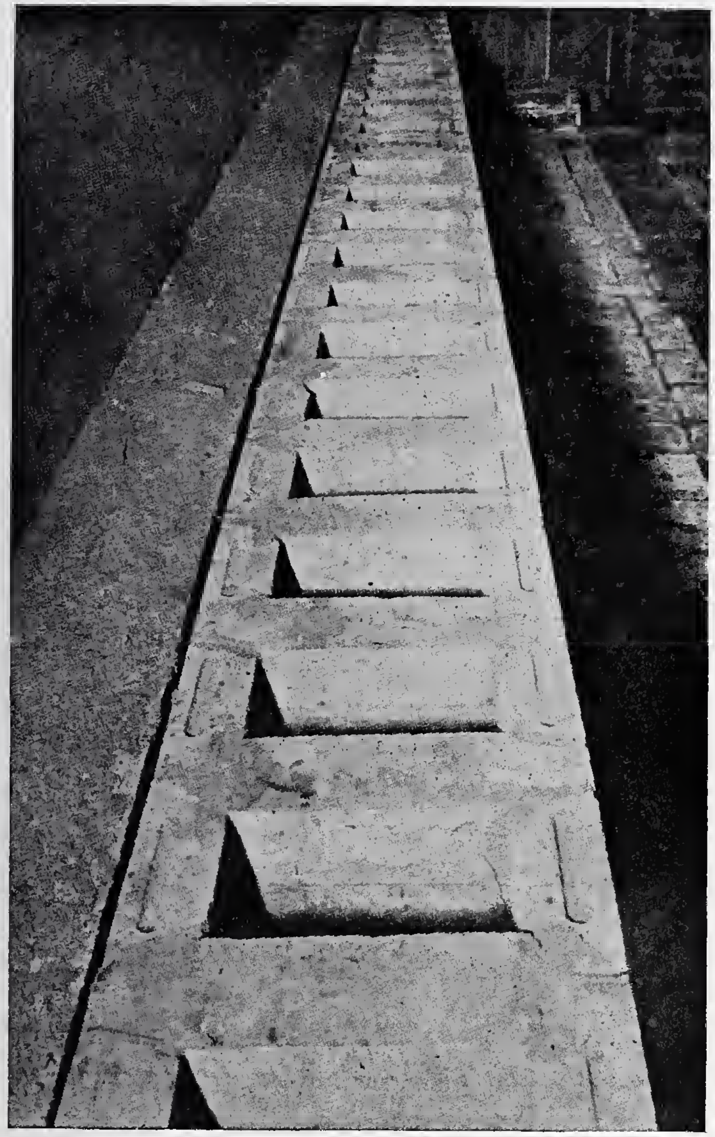

Fig. 67.—Heating Wall of Koppers Rectangular-Flued Oven.

Careful comparison of the relative amounts of combustion in each flue, bearing in mind that the heat of the rectangular flue is divided between two ovens, shows that each triangular flue carries 38 per cent. more heat than one-half of a rectangular flue. As the triangular flue, however, is required to heat a greater wall area, essentially in the same proportion, there is no gain here except through the smaller number of joints and flue partitions in the new system. This feature adds strength also to the oven lining.

It is probable that any gain secured by the triangular system in heating efficiency through the increase of direct heat-transmission surface is counter-balanced in large measure by a loss due to the greater number of gas burners per wall, and consequent increase in gas nozzles liable to carbonizing and in number of points where imperfect air-gas mixing may occur.

Besides a material gain in strength of the wall, due to the lessened number of joints and the bracing effect of the diagonal flue partitions, the principal advantage indicated by the triangular-flued construction lies in the supplementary heating effect from flue to flue given by the overlapping position of each. If a gas nozzle becomes plugged or a single flue for any other reason fails to carry its normal heat, the effect on the inner wall of the oven is likely to be lessened through the supplementary heat of the two closely adjoining flues.

The triangular-flued ovens require no greater weight of brickwork, no more space per unit, and no greater expense (according to designers' claims) for construction, than the previous rectangular flued type.

The Koppers Improved "New Type" Oven.

U. S. Patent 1,374,546 was granted April 12, 1921, to J. Becker (assignor to The Koppers Co.) for a modification of the Koppers regenerative oven, in which the reversal of air and waste gas flow is from the row of flues on one side of an oven to the row on the other side. To accomplish this the hot waste gases from one side are made to pass *over the top* of the oven through several ducts, between the coal-charging holes, and down the vertical flues on the other side.

Referring to the illustrations (Figures 69-72), there are to be noted several characteristic features in the new design: (1) the higher position (by approximately 22 inches) of the horizontal flue in relation to the oven chamber, with correspondingly increased height of the vertical flues, greater depth of coal and taller ovens; (2) small cross-section of the horizontal flue owing to reduction of the requirement for carrying capacity by dividing the flue end-for-end into two or more sections; (3) greater thickness of wall in the region of the horizontal flue, thus increasing strength, and affording heat insulation for the oven tops; (4) concurrent flow in all of the flues of each oven wall during any one period, doing away with the objectionable periodicity end-for-end in the ordinary design.

The improved design is applicable either to the usual rectangular flued wall or to the triangular flued wall. The cross-over flue over-tops each alternate oven only. A layer of special, highly-insulating brick (of infusorial earth, so-called "Sil-o-cel") is used to insulate the oven top in the region of the cross-over flue.

In the usual type of Koppers oven it is necessary to have the horizontal flue large enough in the center to permit free flow of the entire quantity of gases of combustion from the heating flues in either half of the wall. Practically this has required so large a flue, that to avoid overheating of the oven tops, especially at the center, it has been necessary to place the horizontal flue at a level well below that of the coal in the oven. There is thus a tendency toward under-coking of the top portion of the charge, in the time suited to proper coking of the lower portions. There is also a weakening of the wall due to the large size of the horizontal flue.

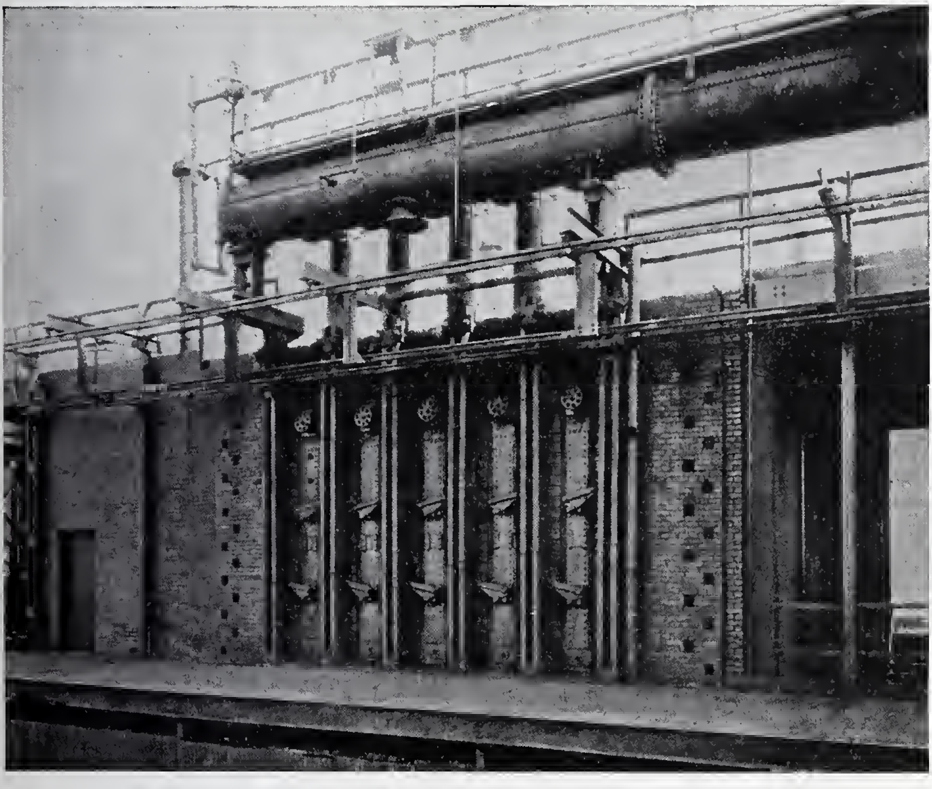

Fig. 68.—Battery of Five Koppers "New Type" By-Product Coke Ovens at Plant of Chicago By-Product Coke Co., South Chicago, Illinois.

The new design, with cross-over flues, divides the horizontal flue into sections, end-for-end, which may be 2 to 5 in number, each bringing together the combustion gases from a small group of vertical flues to a cross-over flue at its center, instead of at the end as in the old type. This makes possible not only a material reduction in size of the horizontal flue, but also the tapering of each section from its center to its ends. There is, furthermore, in the horizontal flue sections much less of a gradation of gas velocity over the respective vertical flues, and therefore less variation in "motive pressure" above the flues requiring compensation by the sliding brick settings (Figure 73). The required draft in the flues is low.

By virtue of its smaller size and heavier walls, the horizontal flue is in the improved oven placed at a higher level, without risk of overheating, and the vertical heating flues are lengthened almost to the top of the coal charge. All these features should make for increased uniformity of heating of the coking charge.

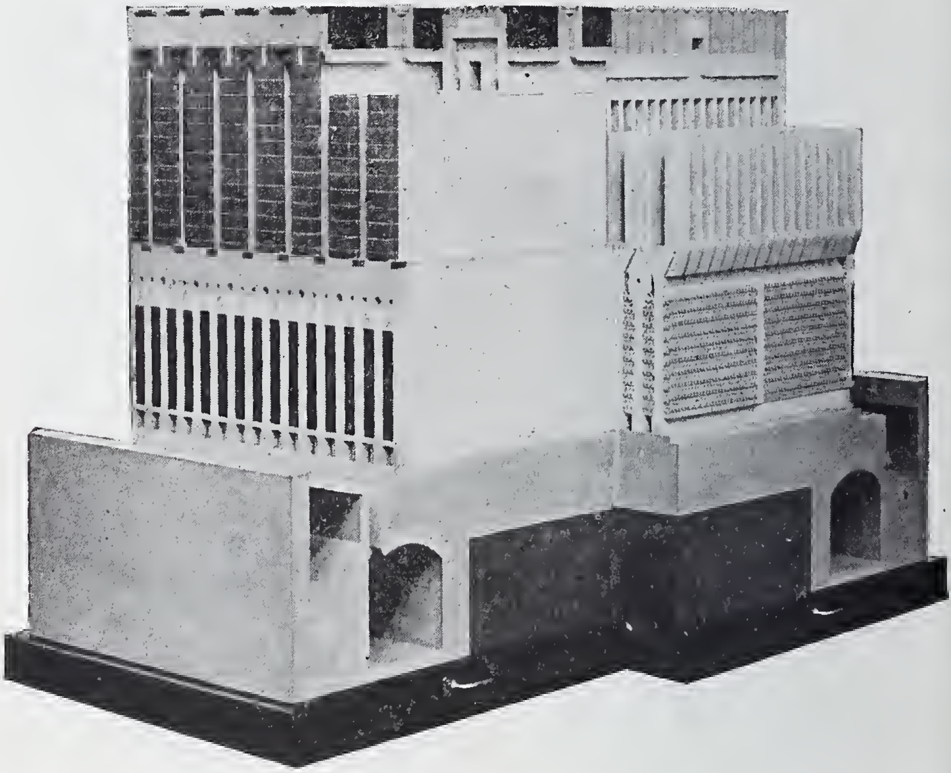

Fig. 69.—Model giving Sectional View of Koppers "New Type" By-Product Coke Ovens.

The new design is especially advantageous when producer gas is burned, since it gives the needed additional flue length and carrying capacity to handle the greater volume of combustion gases obtained from low heating-value fuel gas of this character.

Furthermore, when coke-oven gas is used in the heating flues, mixed with hot returned waste gas (for the purpose of lengthening the flame and distributing its heating effect, as is explained in another chapter, see pp. 255-6, Chap. 10), the new design of flues handles with increased efficiency the larger gas volumes here involved, and promotes thus uniformity of heating.

A great advantage in the new oven lies in the maintenance of continuous heating by concurrent flame flow along the full length of the oven during each period. The tapering oven, which under the old system, involves an irregularity due to the burning of a larger amount of gas at the wider end and the necessity for exchanging the waste heat of this gas with a disproportionate quantity of air at the other end, is much better managed under the new system.[9] (Figure 74.)

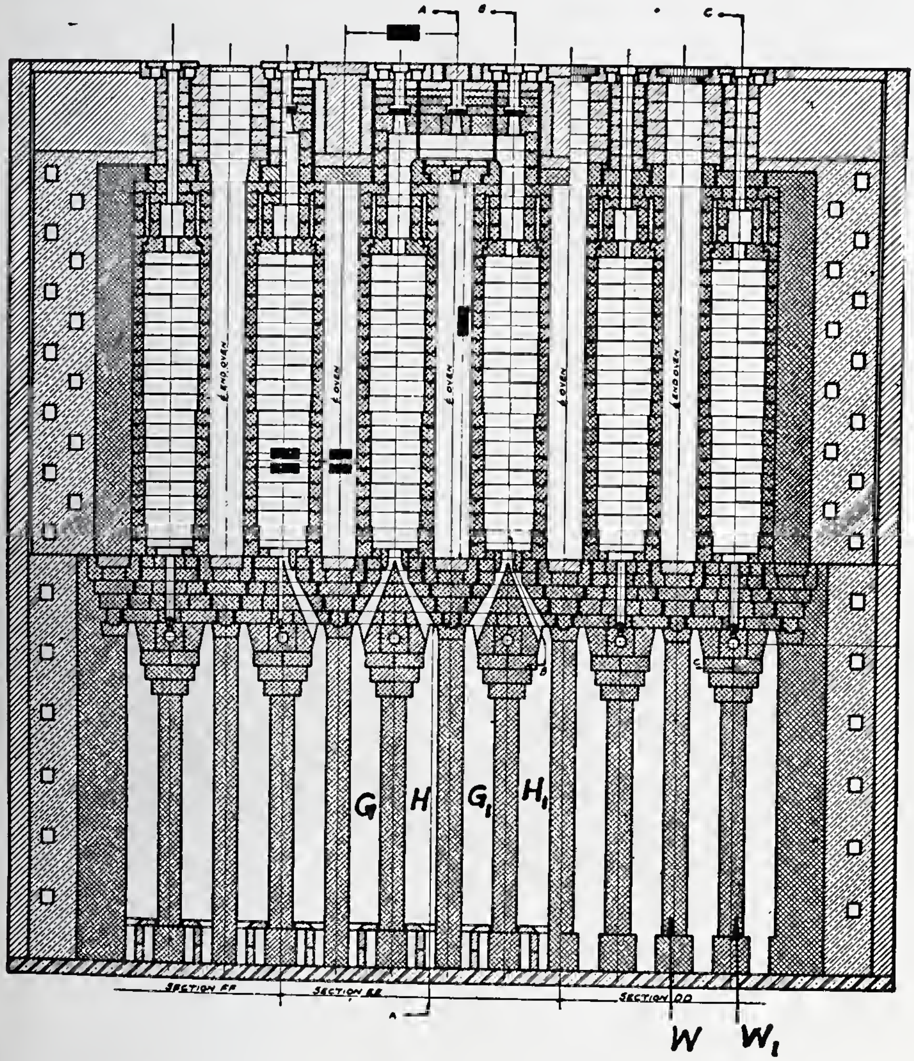

FIG. 70.—Koppers "New Type" By-Product Coke Ovens, Transverse Section.

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[9] On this point, having to do with improved regeneration of air by waste gas, see J. Van Ackeren, "Heat Distribution in New Type Koppers Oven," *Trans.*

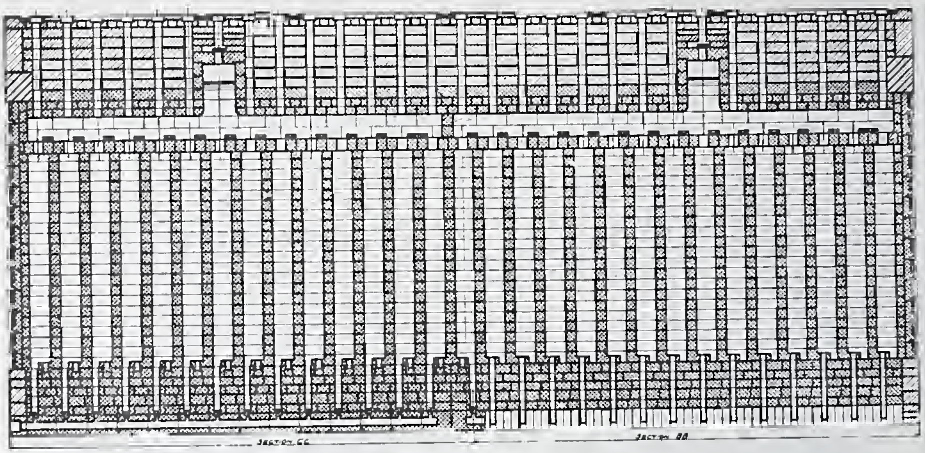


Fig. 71.—Koppers "New Type" By-Product Coke Oven, Longitudinal Section through the Flues.

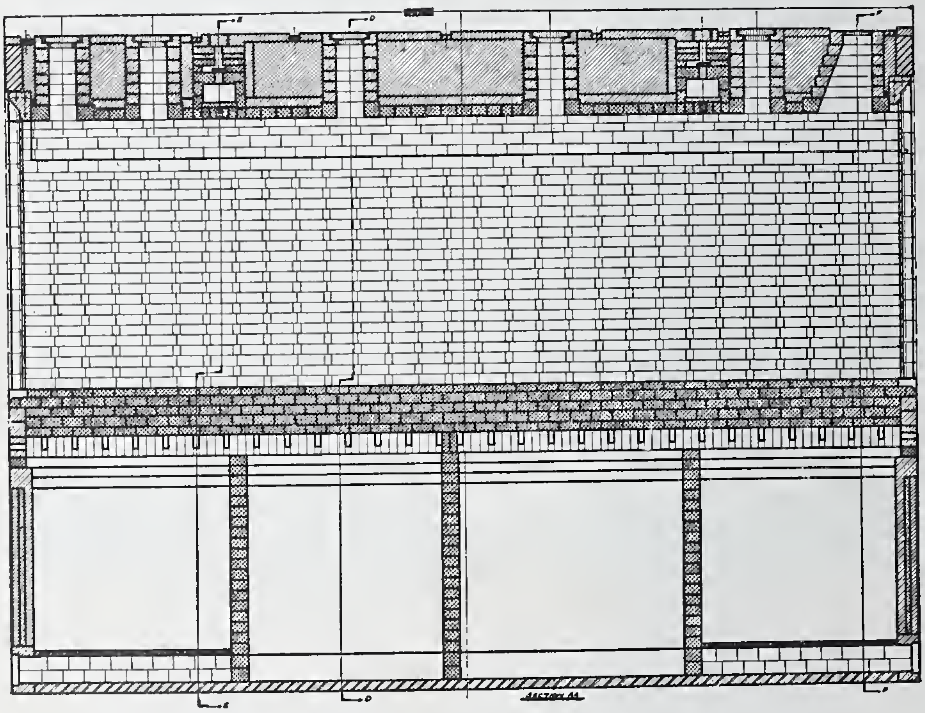


Fig. 72.—Koppers "New Type" By-Product Coke Oven, Longitudinal Section through the Oven.

Substantial load-carrying gas-tight division walls (w, w′, Figure 70) stand underneath both oven chamber and heating wall, separating the

Amer. Inst. Mining and Metallurgical Engineers, 1923, (especially pp. 9-10 of the article). This article is, in general, a thorough exposition of the principles of heating in the new type oven.

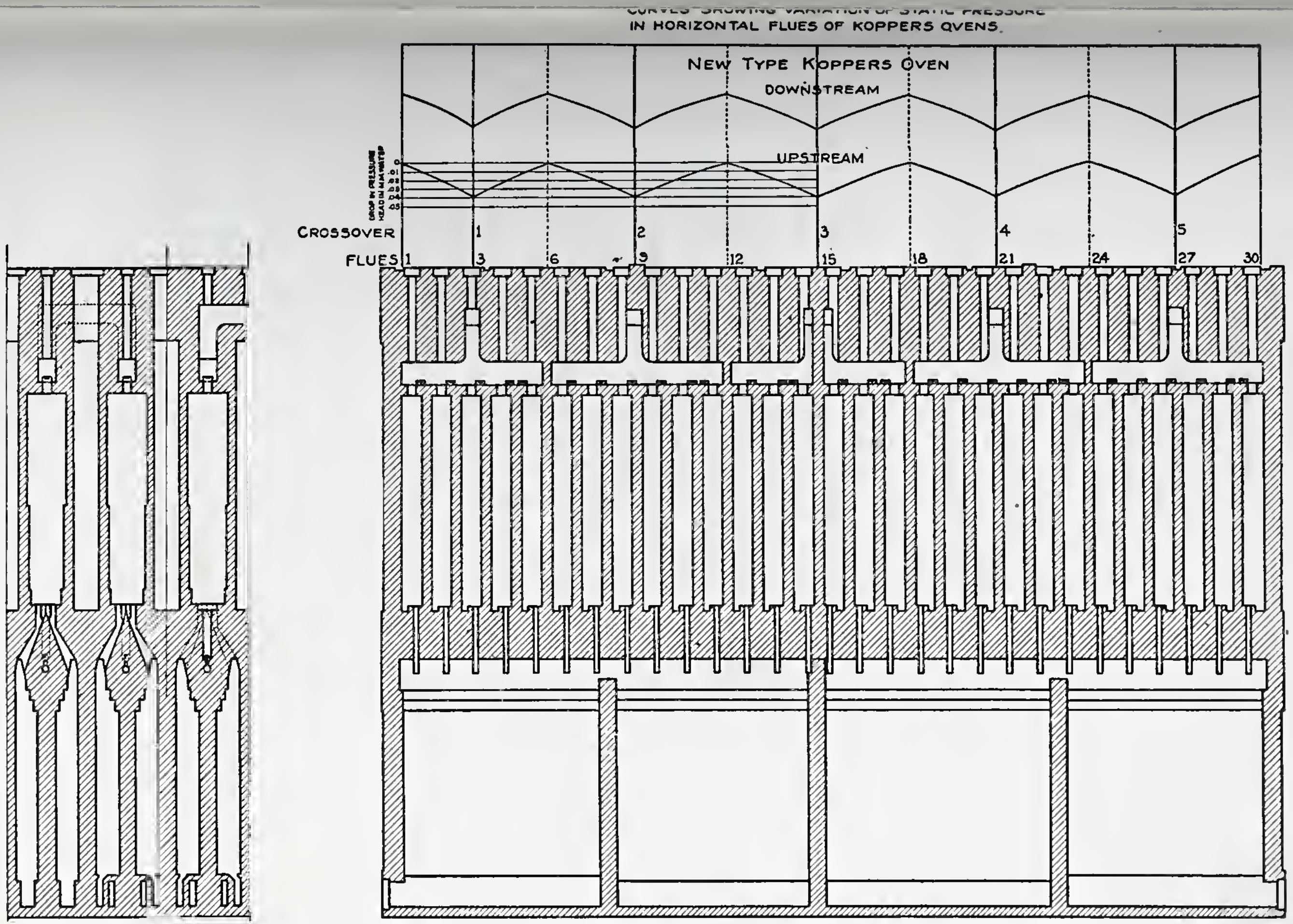


FIG. 73.—Diagram Showing Variation in Static Pressure in Horizontal Flues of Koppers "New Type" Oven (compare with Fig. 64). Diagram by Joseph Van Ackeren.

regenerator chambers. These afford support to the oven battery and are arranged effectively to prevent diffusion of gases from chamber to chamber when varying pressures and different kinds of gas are maintained in adjoining chambers.

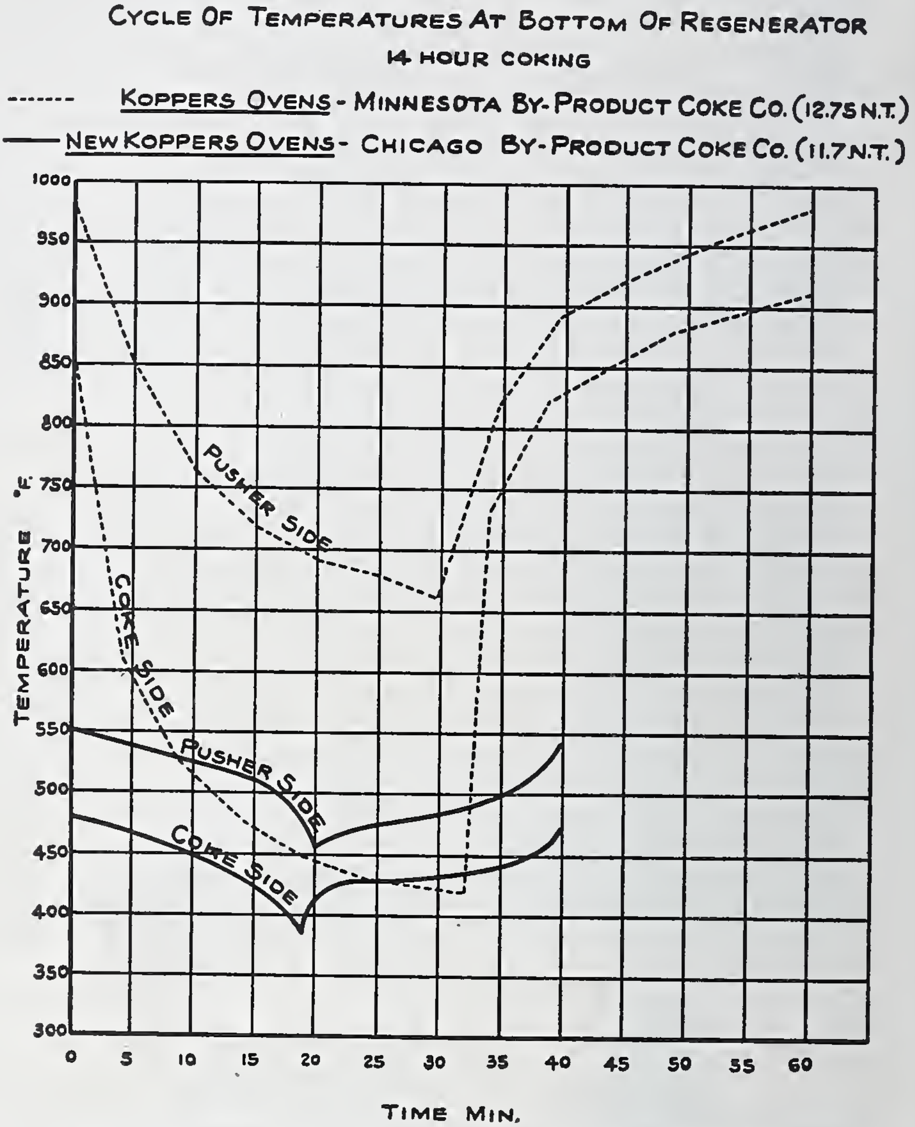


FIG. 74.—Diagram Showing Temperature at Base of Regenerators during Cycle of Reversals; comparing "New Type" Koppers Oven (on 20-min. Reversing Schedule) and "Regular" Koppers Oven (on 30-min. Reversing Schedule). Diagram by Joseph Van Ackeren.

With the improved oven, it is proposed to recommend generally the use of producer gas, or if coke oven gas is used, the admixture with it of waste flue gas. There are two regenerators communicating with each row of heating flues. During one period the two adjoining regenerators, G and H (Figure 70) under a row of heating flues, receive an upward flow of air in G and of producer gas in H or of air in G and cold returned waste gas in H (in case of heating by coke-oven gas), while the two regenerators under the next adjoining heating wall both receive the down-flow of hot waste gases from combustion of this mixture. During the succeeding period the reverse flow occurs.

The Koppers "Gas Oven."

This name is applied to the "two-fold regenerative" oven, essentially the same as the cross-regenerative coke oven already described, except that alternate regenerators or pairs of regenerators preheat fuel gas instead of air. Producer-gas (or blast furnace gas) instead of coke-oven gas is used for combustion in the heating flues, in order to release the entire amount of coke-oven gas, arising from carbonization of the coal, for disposal outside of the plant. Owing to the low heating value, high nitrogen content and consequent low flame temperature of producer-gas, when burned cold, pre-heating is required—both of gas

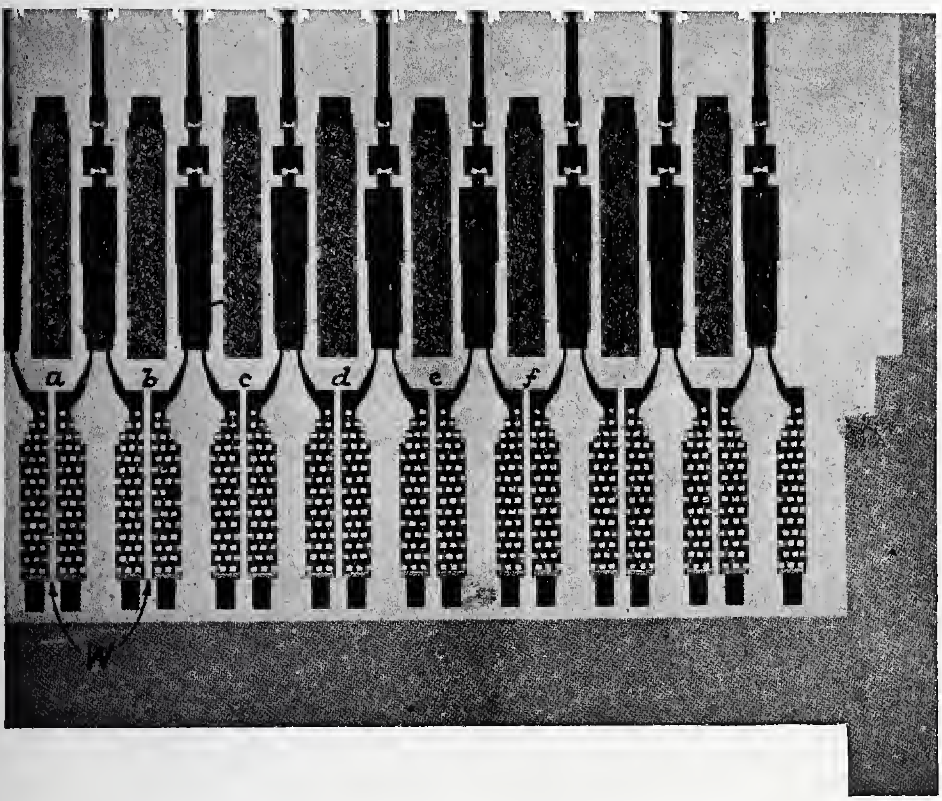


Fig. 75.—Koppers Gas Oven, Transverse Section.

and air—in order to obtain good results. Accordingly the gas ducts underneath the rows of flues are dispensed with, producer-gas is fed directly into the regenerators, and from there to the flame flues.

The illustration (Figure 75) shows the old type end-to-end reversing oven. Assuming that all flues on the observer's side are burning with up-draft, each alternate regenerator (a, c, e, etc.) carries producer gas, admitted from the bottom by a valve communicating with either gas main or chimney flue, while the other regenerators (b, d, f, etc.) carry air admitted as usual by a valve opening to the air or to chimney flue. Alternate ducts from the regenerators carry fuel gas (or air) to the rows of flame flues on either side of the oven. After reversal, all of the regenerators (on this side of the battery) carry down-flow of hot waste gas. Formerly, in the Koppers "gas oven," double regenerators were used, heavy gas-tight divisions walls, underlying the flues, were provided to separate compartments in which different gases passed, while lighter division walls (w, Figure 75) separated those chambers carrying similar gases. The more recent installations dispense with this light division wall.

The gas ducts and nozzles under the vertical flues may be retained, to use for burning coke-oven gas when desired (in event of a slackened market for gas), and the so-called "Combination Oven" results, suited for either producer gas or coke-oven gas heating.

The Koppers Small Oven Gas Plant.

As adapted to the needs of city gas plants of the lesser capacities, a Koppers oven of reduced length and width, and lower operating costs, is coming into use. With ovens thus reduced in size, the minimum plant suited to economical operation is much smaller than with the standard ovens. This type of oven is 19 feet long, 12 to 14 feet high, and 12-14 inches in width. The charge of 7.6 tons of coal may be coked in 10-12 hours.

Owing to the short length of this oven, a comparatively small and light-weight pusher machine may be used, and other accessories and machinery are correspondingly small and less costly. The coke quenching car may be dispensed with, and quenching done on an inclined wharf with a hose.

Figures 76-78 illustrate the design of this oven. Alternate regenerators are arranged for admission of producer gas or air to be preheated, each chamber delivering the gas (or air) to two rows of heating flues. There are provided also the usual gas-ducts below the flues, for coke oven gas, if desired.

In the vertical section, Figure 76, may be seen the connections to gas ducts and regenerators, a new and distinctive feature of this oven being the arrangement of all fuel gas supply lines and waste gas flues on one and the same side of the battery, thus simplifying and facilitating operation of the ovens.

Such a plant, of say 10 ovens, may be operated so as to vary its gas output from 500,000 to 1,500,000 cubic feet per day, to suit a variable demand (for either gas or coke), by varying the coking rate, and by changing from coke-oven-gas heating to producer-gas heating.

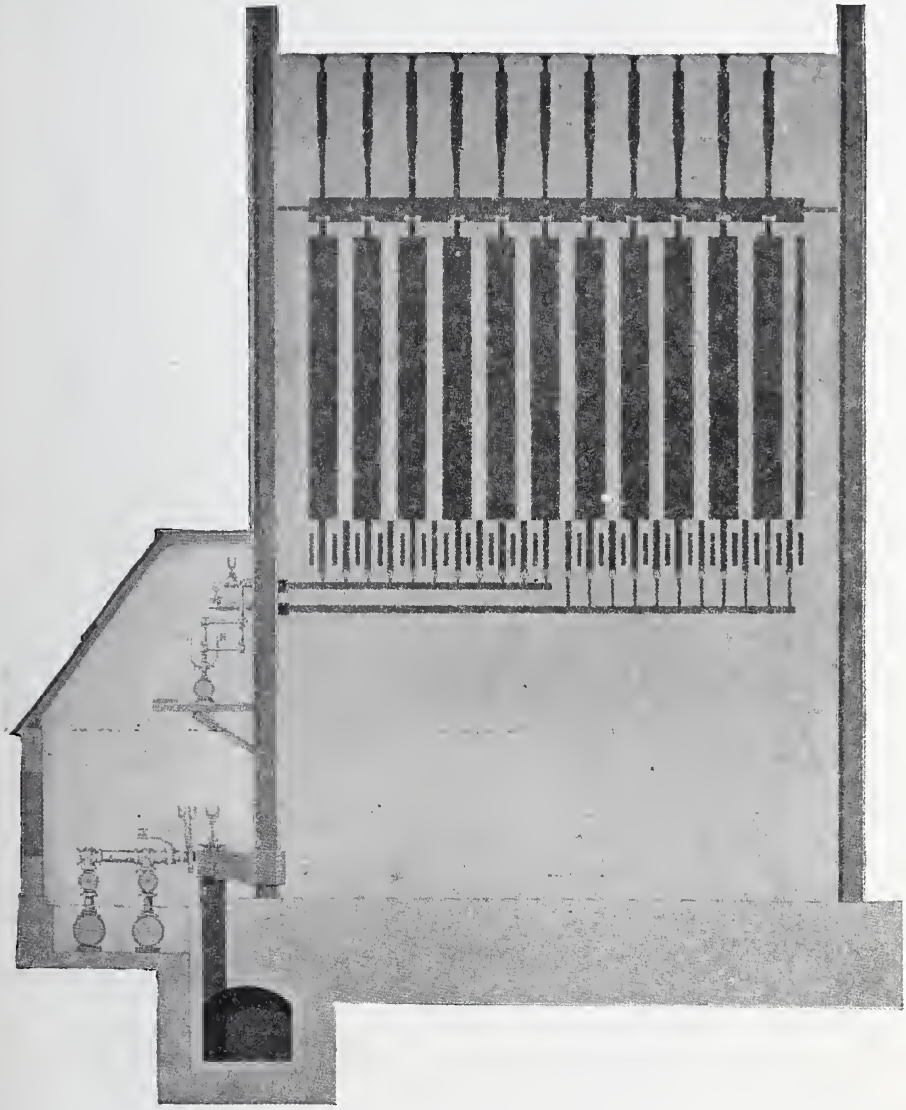


FIG. 76.—Koppers Small Gas Oven, Longitudinal Section through Flues.

The Koppers Waste Heat Oven.

Although not, at the time of this writing, used in America, a non-re-generative waste-heat oven of the Koppers type has been designed and built. All of the vertical heating flues in each row, except two at one

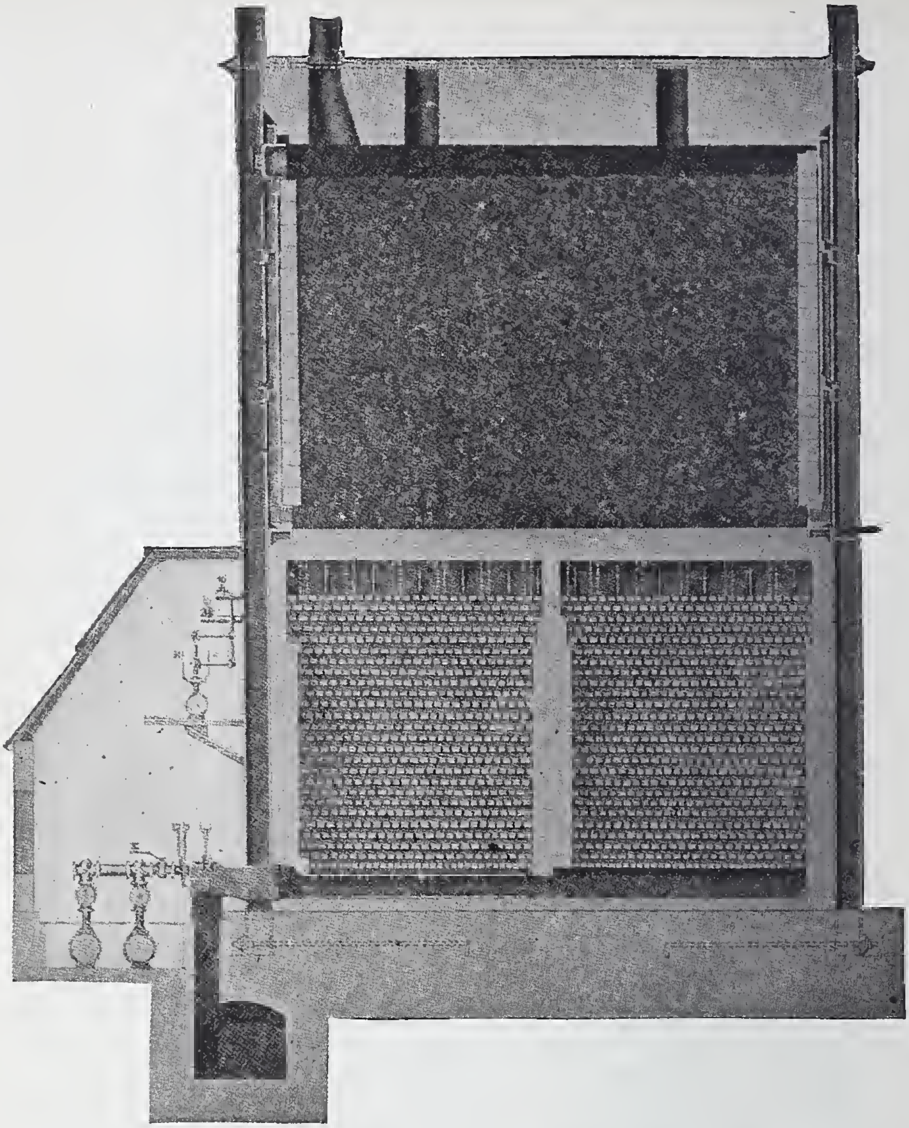


Fig. 77.—Koppers Small Gas Oven, Longitudinal Section through Oven.

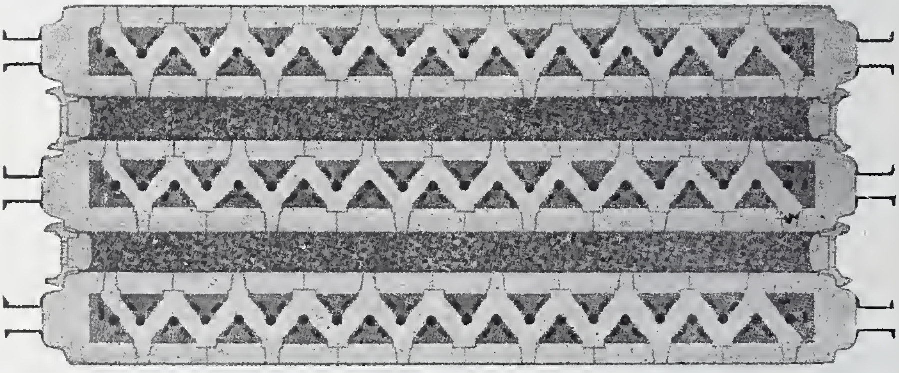


Fig. 78.—Base of Flues, in a Koppers Triangular-Flued, Small Gas Oven (showing gas and air inlet; compare with Fig. 62).

end, carry continuous upward flow of burning gases, leading to the common horizontal flue and thence downward through two flues at one end into the large waste gas flue, to waste-heat boilers, and finally to the chimney.

Fuel gas is supplied to the vertical flues, as in other Koppers ovens, through nozzles from a gas duct lying below each row of flues. Air enters from a large flue, or duct, below and longitudinal to the battery, into a sole flue directly beneath each oven, whence by lateral ports it reaches the vertical flues. Draft on each oven is regulated by a damper at the base of the down-coming flues, and on each vertical flue by the sliding brick at top, as in other Koppers types.

The Wilputte Cross Regenerative "Air-Dosed" Oven.

The coke oven of the Wilputte Coke Oven Corporation[10] was adjudged, May 22, 1919, by the U. S. Circuit Court of Appeals, an infringement of H. Koppers' U. S. Patent 818,033 (1906), but had, prior to that decree, been built at a number of plants in the United States and Canada. It is essentially the same, above the level of the oven floor as the Koppers oven.

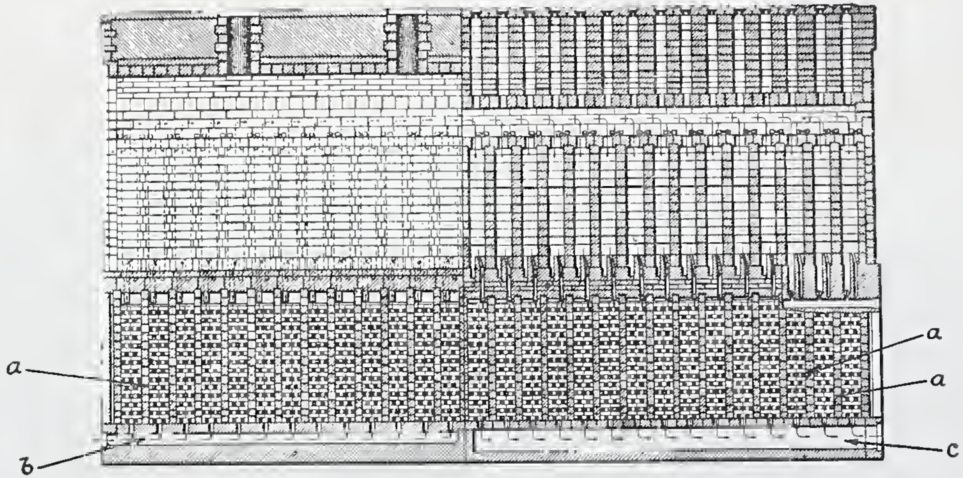
In the structure of the regenerators and the mode of operation to supply preheated air to the flues, it has, however, distinctive features. From the cuts (Figures 79-80) it may be seen that individual regenerators underlie the ovens in position parallel to them, and the regenerators communicate directly with the heating flues by passages individual to each. In these particulars the oven follows Koppers' design, and mainly on that ground has been adjudged an infringement in the decree above referred to.

The Wilputte oven, however, modifies the Koppers design by still further individualizing the regenerators, making a separate regenerative chamber for each flue by placing vertical transverse division walls in the regenerator space underlying each oven. An air pipe (b) lying at the bottom of this row of regenerative compartments communicates with each by a variable opening so that each compartment and each flue receives a "dose" of air, varied to suit its relative position and flow-resistance. The air is forced to the regenerators under the positive action of a blower.

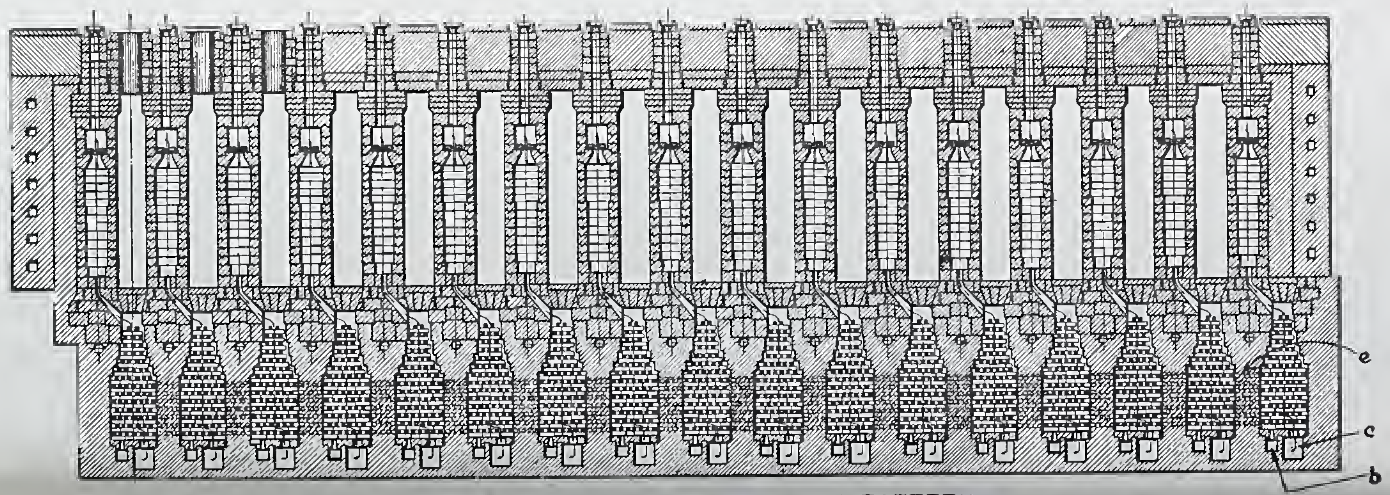
On reversal, the waste gases passing downwards issue from the compartments through graduated openings into a duct (c) below the regenerator leading to the chimney flue.

Another distinctive feature of the Wilputte regenerating system lies in the so-called "equalizing" ports (e, Figure 80) connecting the regenerator compartments under one oven to the adjacent ones under the next oven. It is held by the infringement decree above cited that these ports perform no equalizing function, inasmuch as each compart-

[10] United States Patents 1,212,865-866, Louis Wilputte, January, 1917.



SECTION CROSSWISE OF OVEN BATTERY



SECTION LENGTHWISE OF OVEN BATTERY

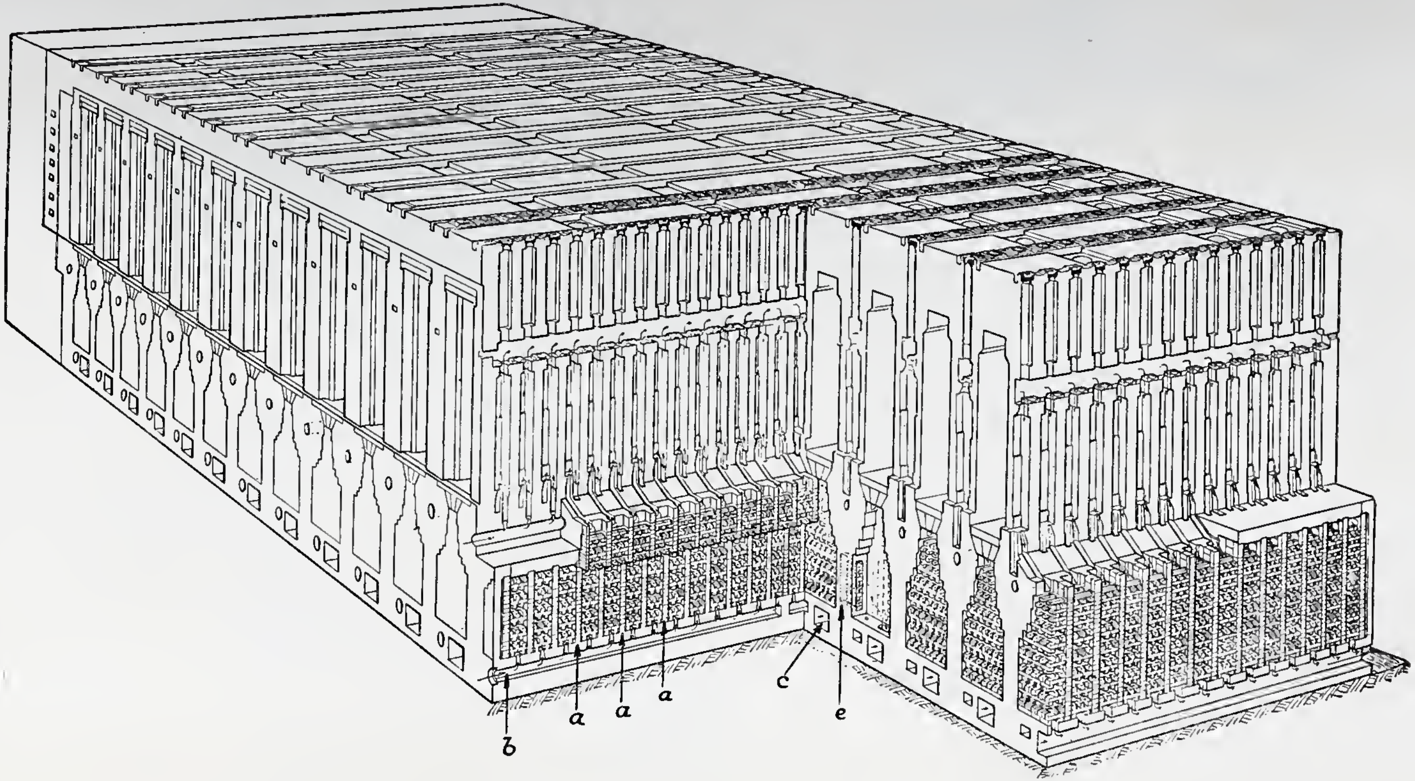


Fig. 80.—Wilputte By-Product Coke Oven Battery, Sectional View in Perspective.

ment is designedly "dosed" with its proper amount of air, making impossible any distribution from one compartment to another, and that therefore the ports do not, as claimed, function so as to convert the regenerators from their individual character, paralleling each oven chamber, to that of a compound or common regenerator for the battery, transverse to the ovens.

The Otto-Hoffman and Related Systems of Regenerative By-Product Coke Ovens.

A large number of ovens of this type, modified in various degrees, have been built in America. One of the earliest by-product coke plants in the United States, viz., that of the Cambria Steel Co., at Johnstown, Pa., built in 1895, was of the Otto-Hoffman type.[11] The oven originated in Germany.

The Otto-Hoffman oven (Figures 81-82), is heated by vertical flues, one row between two ovens imparting heat to both. In the regenerative ovens, the flow of burning gas is reversed from end to end, as in the Koppers type, that is, from the half of a row of flues at one end to the half at the other. In the arrangement of regenerators, in the method of supplying air and gas to the flues, and in control of draft, however, this type of oven differs essentially from the Koppers.

Long regenerators, common to the entire battery of ovens, are placed, one on each side, transverse to the ovens. Leading from the top of these are ports, usually one for each oven (a, a, Figures 81-82) (although in some American installations one port from the regenerator has been made to serve three ovens, see Figure 85), this port conducting the preheated air into one end (the outer) of a sole flue (b) under the oven, from which, by lateral ports (c, c) (one for each vertical flue) the air passes into a "combustion chamber" (d) directly under the row of heating flues. There it meets fuel gas for combustion. The burning gases then pass up the vertical flues of one half of the row, along the horizontal flue (e) and down through the other half, issuing through the combustion chamber and sole flue on that side into the other regenerator.

The fuel gas, in the later Otto types, is admitted to the bottom of the combustion chamber (d, Figure 82) by a plurality of burners (3 to 6) on each side of the oven-center, usually from below, although in the original Otto Hoffman design there was but one burner on each side, this being at the outer end of the combustion chamber. Regulation of the gas admitted at these different burners affords control of the heat in different parts of the oven.

The sliding damper (A) (Figure 82) over the air port from regenerator affords control of the draft (or air) on each oven as a whole.

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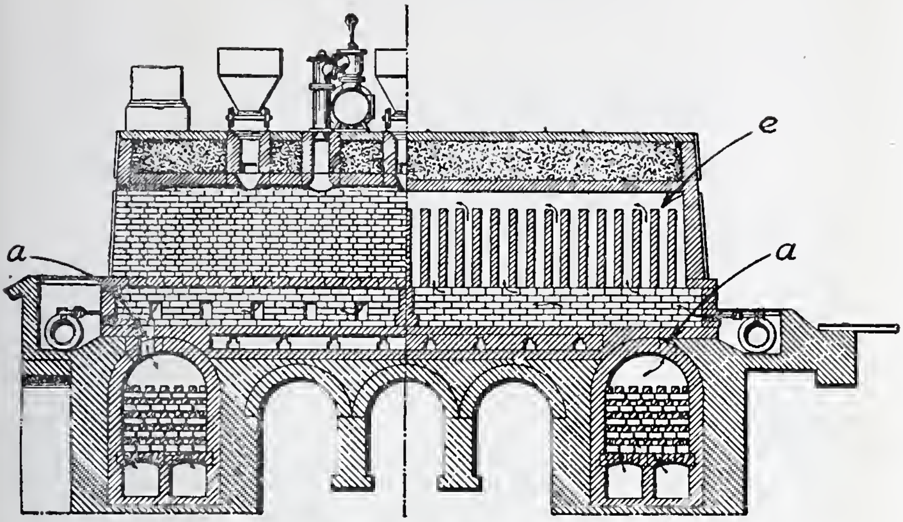
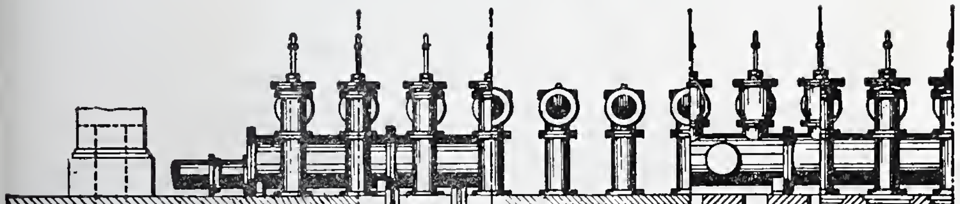
[11] Some of the later portions added to this plant have been modifications of the old Otto-Hoffman-type, designed by the Cambria Steel Co., and called locally the "Cambria Oven." (See below, p. 215.)



Longitudinal Sections.



Section Through Regenerator. Elevation. Transverse Sections.

Fig. 81.—Old Type Otto-Hoffman By-Product Coke Oven, Longitudinal Section Above, Transverse Section Below.

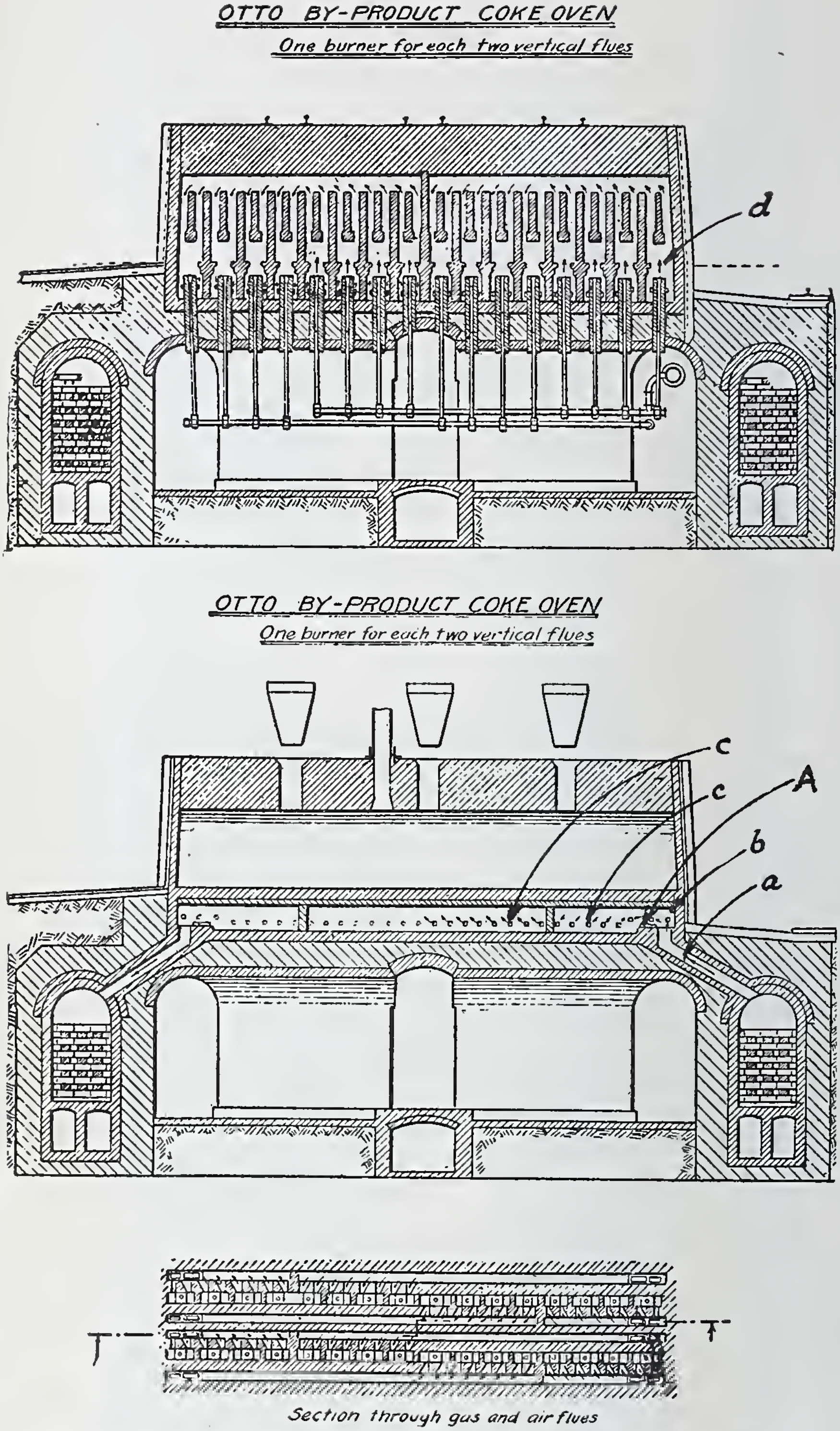

OTTO BY-PRODUCT COKE OVEN
One burner for each two vertical flues
d
OTTO BY-PRODUCT COKE OVEN
One burner for each two vertical flues
c
c
A
b
a
T
T
Section through gas and air flues

FIG. 82.—Otto By-Product Coke Oven, with Modifications by Hilgenstock, Longitudinal Sections through Flues (above) and through Oven (below).

Reversal of air, and of waste gas flow, is made after each period by dampers at the end of the battery, where the two chimney flues from the regenerators on either side of the battery meet the main stack flue and the air supply flue, to either of which they may be connected in alternation by the reversing damper.

The Otto ovens are ordinarily provided with air supply under pressure of a blower.

There are to be noted certain fundamental differences between such heating systems as the Otto-Hoffman, and that of the later type of vertical flued oven developed by Koppers. The common or "bus" flue below each oven in the Otto types, through which air is supplied to the vertical flues, is replaced in the Koppers by direct communication from the regenerator to each vertical flue; and to accomplish this, structurally, the regenerators are made separate and individual to each oven and placed in parallel position directly underneath the full length of the oven. In the "bus-flue" type, such a flue receives air at one end and offers varying motive pressures at the successive off-takes along its length where the air is ported to the vertical heating flues. There is a tendency, therefore, toward unequal flow of air through these lateral ports, which difficulty, in the Koppers type, there is an attempt to avoid by regulation at the top of the flues by the sliding brick dampers, and by distribution of the air evenly in the individual regenerator preparatory to direct passage into the flues.

The Otto battery in later designs is provided with working space below for access to gas and air control. The battery structure is supported on a steel platform held by columns of steel or concrete, the platform being protected by "cooling flues" in the brick-work above. The long regenerators rest on support entirely independent of the battery structure. (See Figure 84.)

At many of the Otto installations the weight of the coal larries and their tracks is carried by overhead steel trusses resting on the pinion walls at either end of the battery. This relieves the burden on the flue walls between the ovens, which in this type of oven are not as firmly supported from below as in those types having more solid masonry in the sub-structure in the shape of regenerator division walls.

The Otto-Hilgenstock Oven. Hilgenstock[12] improved the design by introducing several gas burners from below into the combustion chamber instead of one at either end, and by moving the regenerators out to either side of the battery (see Figure 82), thus opening a free space below the battery for control of gas and air inlets. By use of underfiring it was made possible to increase the length of the oven, the old design with one end burner being limited in this respect.

The Otto-Schniewind Oven. In 1901, Dr. F. W. C. Schniewind, technical director and executive for many years of the United Coke & Gas Co., of New York, and moving spirit in the development of the

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[12] U. S. Pat. 649,450 (1900).

Otto coking systems in the United States, secured a patent[13] for a modification and improvement of the Otto-Hoffman oven. In this (Figures 83-85), the combustion chamber below each half of the row of heating flues is divided into 4 (or 5) parts (d_1, d_2, d_3, d_4) in an endeavor to secure uniform distribution of the heat in the flues. Each of the 4 (or 5) combustion chambers communicates with 4 (or 5) flues above, and into each chamber a gas burner enters from below. Air is admitted into each by two lateral ports from chambers, e e, just below the oven sole. The regenerators are placed along the center of the battery and communicate by vertical passages to the *inner* ends of the oven sole flues. In these vertical passages are regulating valves.

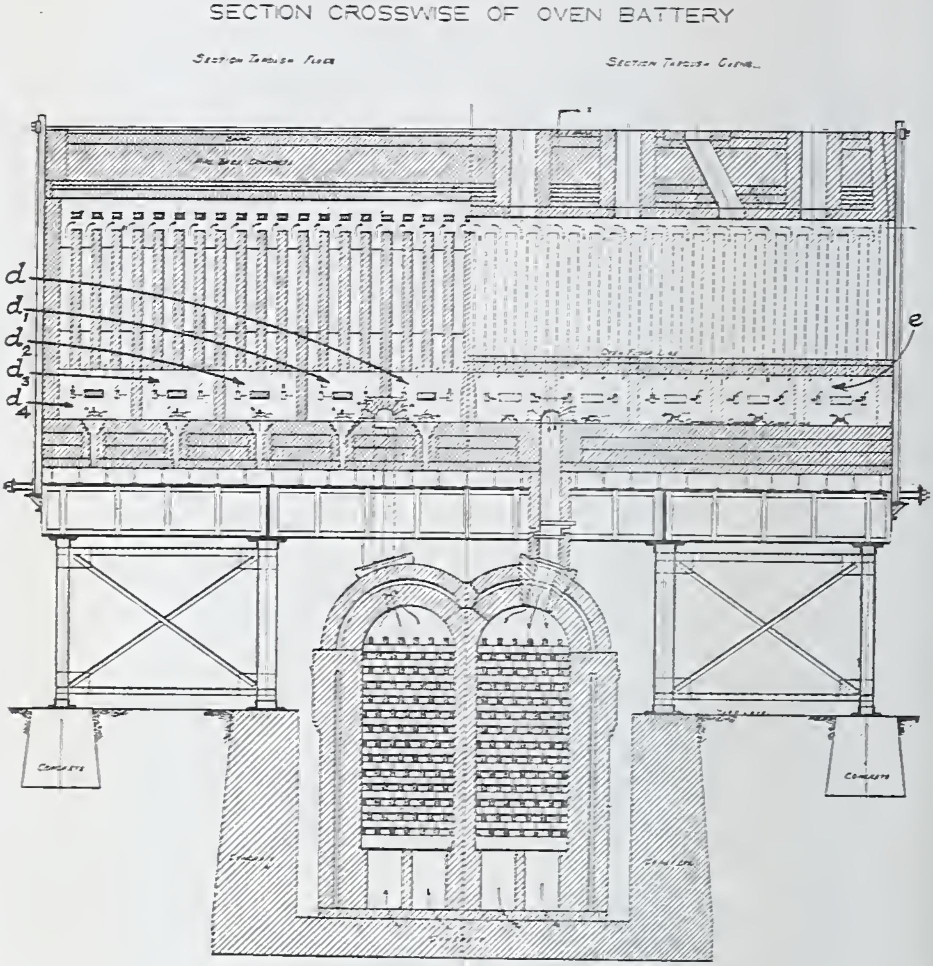

FIG. 83.—Otto-Schniewind By-Product Coke Oven, Longitudinal Section.

The Schniewind oven has been built of unusual length at certain

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[13] U. S. Pat. 673,928 (1901).

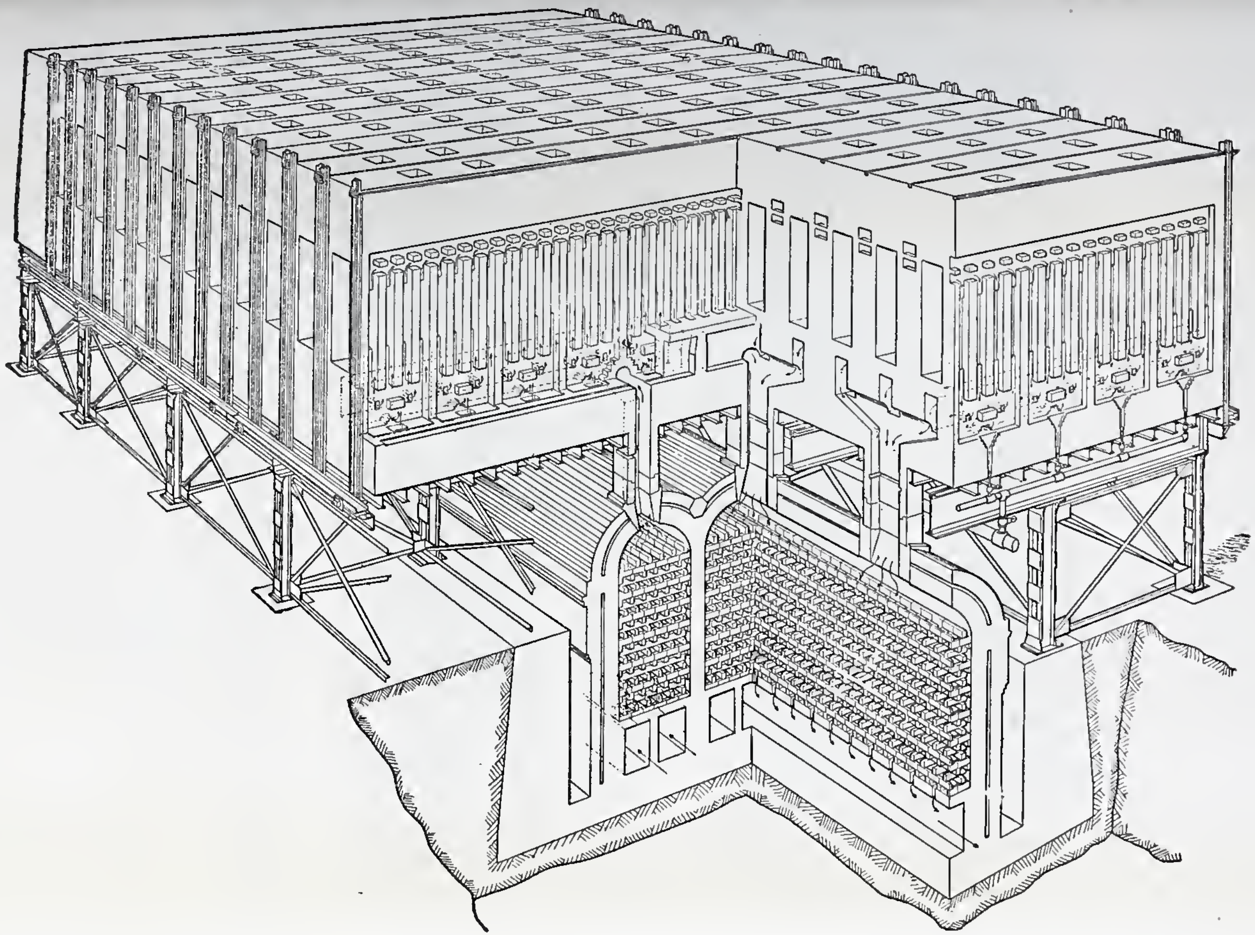


Fig. 84.—Otto-Schniewind By-Product Coke Ovens, Perspective Sectional View of Battery.

installations in the United States, e. g., at the plant of the Carnegie Steel Co., South Sharon, Pa., where the original ovens were 43 feet long. It was found at this plant that with this type of heating system the additional length gave no practical advantage in daily output, or in yields of gas, in comparison with Otto ovens of the more common length of 33-37 feet.

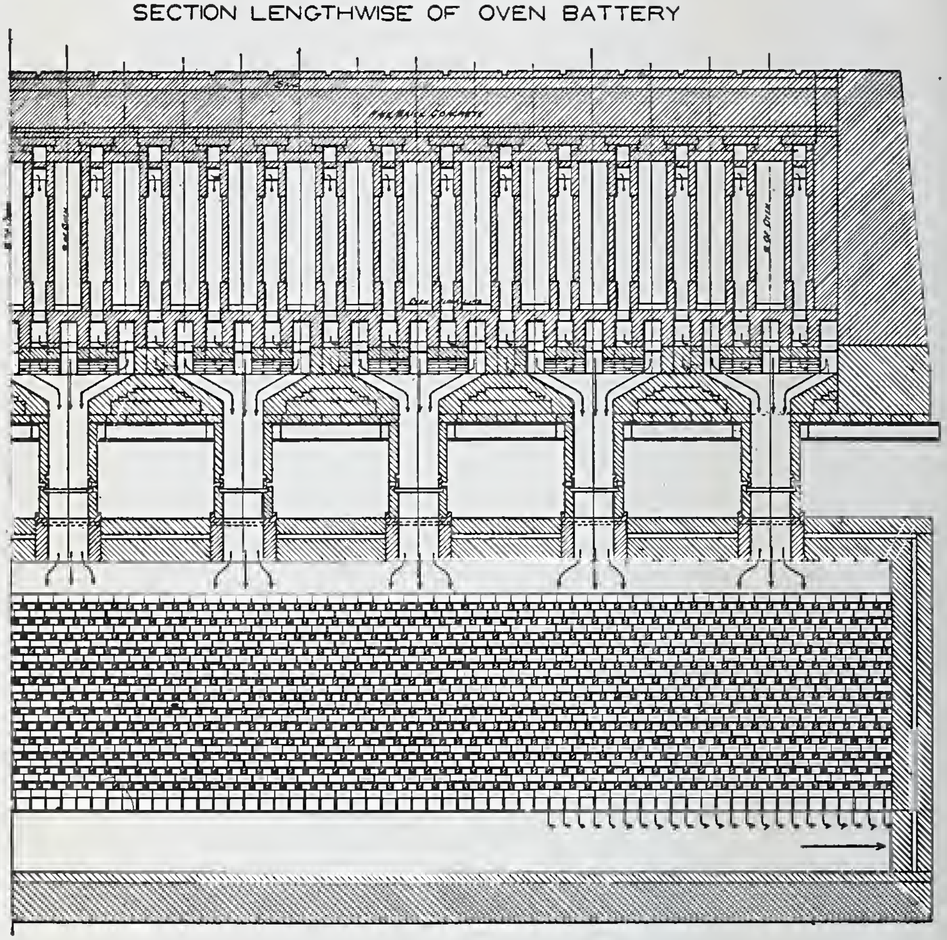
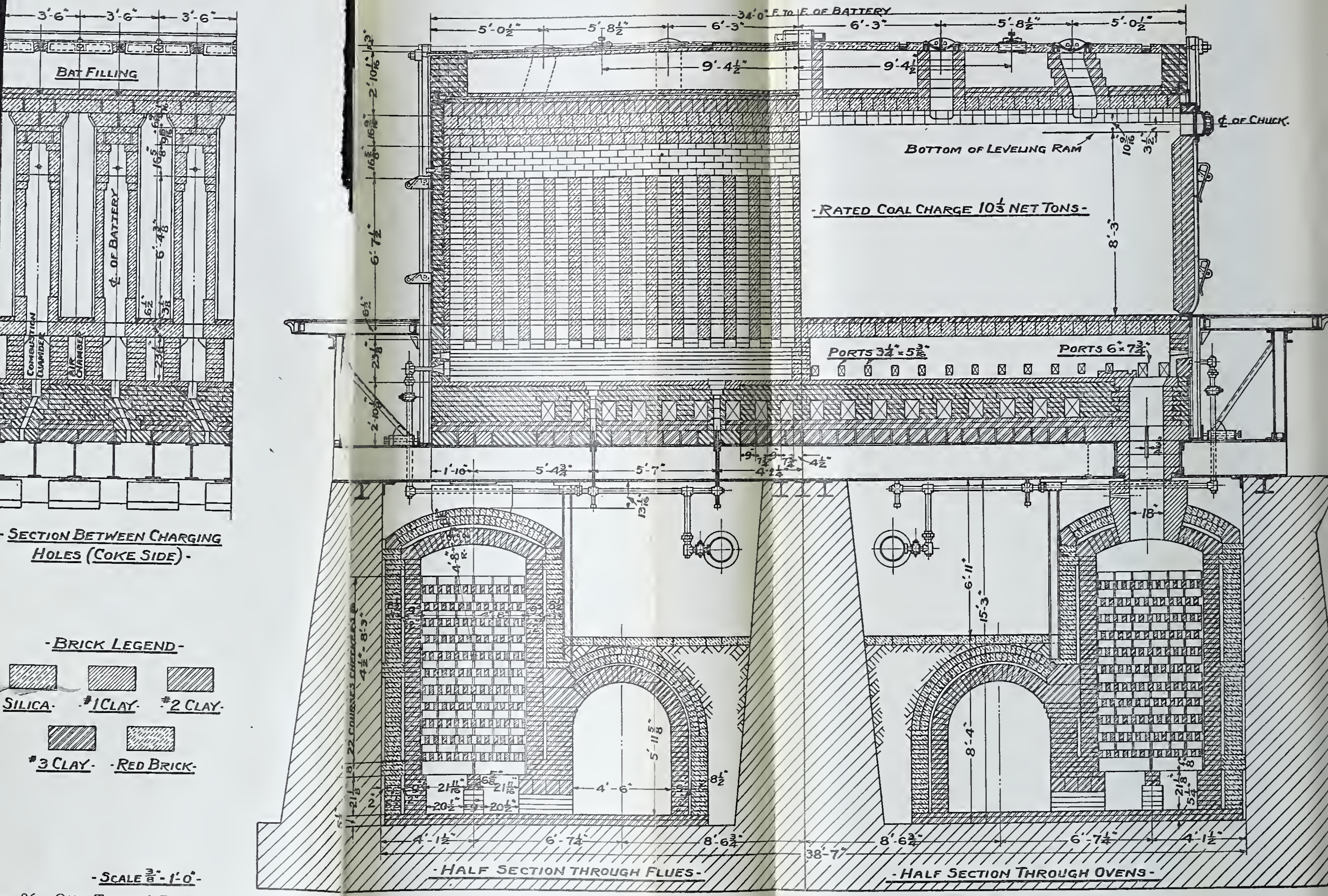


Fig. 85.—Otto-Schniewind By-Product Coke Ovens, Section Transverse to Ovens.

The United-Otto Oven. Under this name the United Coke and Gas Co., of New York, installed a number of coke oven plants in the United States during approximately the period 1900-1907, embodying some of the features of the Otto-Hilgenstock oven and other improvements.

Among the most recent of the installations of the Otto type of oven in this country (at present writing) is the plant at Mayville, Wisconsin (affiliated with the Steel & Tube Co. of America and Milwaukee Coke & Gas Co.). Figure 86 reproduces an actual construction draw-



G. 86.—Otto Type of By-Product Coke Oven, a Built by Northwestern Iron Co. (now Steel & Tube Company of America), at Mayville, Wisconsin. Detail drawing furnished by courtes Milwaukee Coke & Gas Co.

ing of the detail of these ovens. In two later batteries built at this plant a modification of the design has been made, whereby the horizontal flue is lowered a distance of 18 inches, thus shortening correspondingly the vertical heating flues. The object of this change was to avoid over-heating of the oven tops.

The "Cambria" Oven (Otto-Hoffman Type). The Cambria Steel Co., Johnstown, Pa., the original users of the Otto oven in America, have, in successive additions to their plant, modified the original design materially. Although this improved design has been styled locally the "Cambria" oven, it remains essentially the Otto type. Details of the design are not available for publication, but it is known that the oven itself does not differ essentially from the various improved Otto types described in foregoing paragraphs, the regenerators, however, being arranged on a different plan resembling that of other coke-oven systems.

The Piette Regenerative By-Product Coke Oven.

A system of by-product ovens recently introduced into the United States, of the vertical flue type, and embodying elements of design similar to those of both Otto and Koppers, is the *Piette,* of the Belgian-American Coke Ovens Corporation, New York. A battery of 8 ovens was installed at St. Louis, Mo., in 1920-21, for demonstration purposes, and was later taken over by the LaClede Gas Light Co., as an addition to their existing plant.

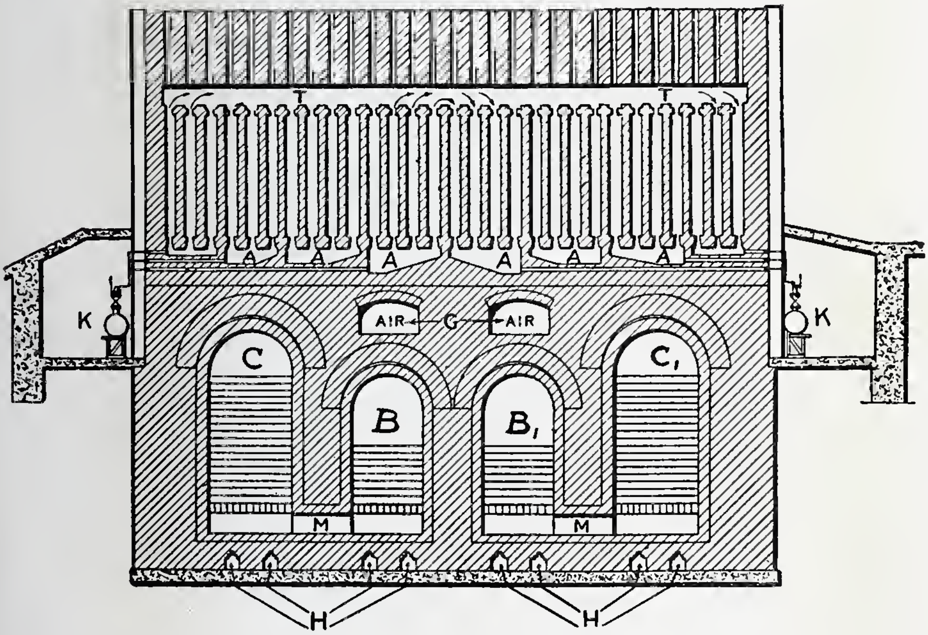


Fig. 87.—Piette By-Product Coke Oven, Longitudinal Section through Flues.

The Piette system embodies long regenerators, common to an entire battery of ovens and longitudinal in respect to the battery; it has also, for conducting preheated air to the vertical flues, an air chamber, sole flue, or bus-flue, directly underlying each oven floor. In these features it is like the Otto system. Gas is admitted through individual nozzles at the base of each flue, where air likewise enters, and the burning gases pass from the tops of the vertical flues, into the horizontal flue, through openings of graduated size subject to inspection from the top of the battery, all of which features are like Koppers. The "combustion chambers" of the Otto types are absent. Combustion begins at the bottom of each vertical flue as in Koppers. Reversal of heating flames is from end to end of each row of flues, as in Otto and Koppers.

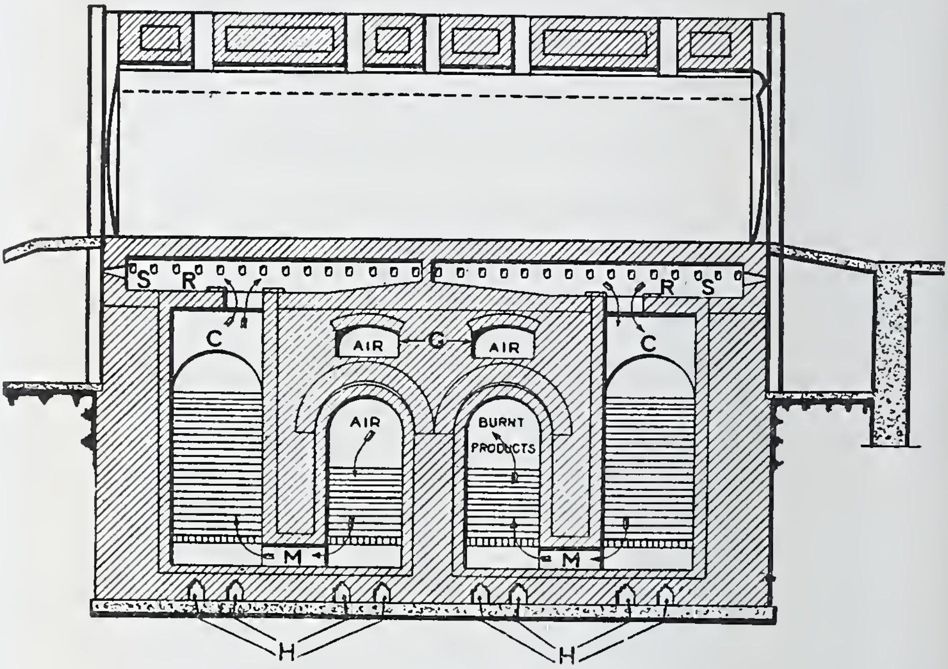


Fig. 88.—Piette By-Product Coke Oven, Longitudinal Section through Oven.

In the illustrations (Figures 87-89) there may be seen several distinctive features. Fuel gas is admitted under each heating wall through a number of channels (4 to each half of the wall), each channel having an inlet regulable outside of the battery, and each channel terminating within, in a chamber (A, A, A) communicating with 4 (or 3) vertical flues above it by graduated nozzles. From the air chamber (S) under the oven sole there are ports also graduated leading to the heating flues. The regenerators, primary C and C_1 (Figure 87), and secondary B and B_1, are underneath the battery in position longitudinal to it. During any one period air is entering on one side only (say, through C_1 and B_1), and waste gases are issuing through the other, B and C.

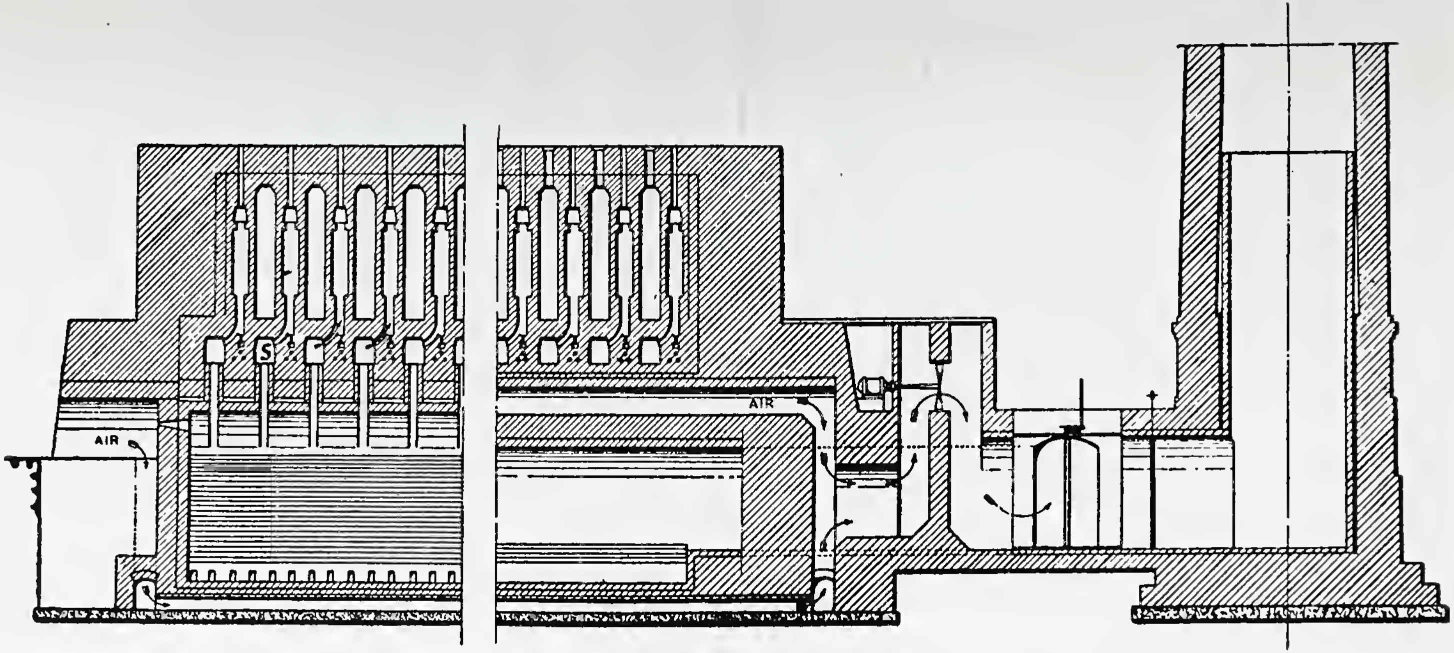


FIG. 89.—Piette By-Product Coke Ovens, Section Lengthwise of Battery, showing course of air and waste gases.

Air enters secondary regenerator B at one end, preferably blown by a fan, passes along the free space in the upper part, (these secondary regenerators (B, B_1) being filled only to about one-third of their depth with checquers), and passes downward and through separate openings (graduated in size) into the bottom of the primary regenerator (C).

It is claimed as a special distinguishing feature of this system, covered by patent, that the regenerators, although longitudinal to the battery, act transversely in transmitting air to the individual ovens. Into the sole flue (S) of each oven there opens a dampered port from the top of the regenerator, this being above and in line with the air inlet at the bottom of the regenerator. A transverse current of air thus passes upward through the regenerator in accordance with the relative draft on each oven.

The air is first warmed in flues G, G, and H, H (Figure 88) from which it is drawn by the fan (Figure 89) and blown to the secondary regenerator, thus recuperating the heat radiated respectively from oven soles and from bottoms of the regenerators.

An unusual degree of stability of structure is claimed for this type of oven battery in that the supporting walls, parallelling the regenerators, are longitudinal to the battery and at right angles to the axis of the ovens; also that the brickwork of the regenerators, affected by unequal expansion due to periodic temperature changes, is structurally independent of the oven brickwork above.

The Foundation, or "American," Regenerative Coke Oven of The Foundation Oven Corporation.

This oven, designed comparatively recently by American engineers, has been installed at the plant of the Granby Consolidated Mining, Smelting and Power Co., at Anyox, British Columbia, by the Foundation Oven Corporation, of New York. It presents certain distinctive features designed to promote uniform heating of the oven walls, provide direct control of heat distribution, and to eliminate some of the elements of structural weakness in other oven types.

The oven is 38 feet long, 10 feet 8 inches high, and tapers from 17 inches to 15 inches in width. The heating flues are vertical, one heating wall standing between two ovens, as in the Koppers and Otto types; but there is no continuous horizontal flue, at the top of the heating wall, to weaken the structure and to be burdened with the passage of the aggregate of combustion gases from the entire row of flues. The up-going flame in each alternate flue turns at the top and descends in the immediately adjacent flue, there being, in effect, a series of pairs of flues, often referred to as of the "hair-pin" type. On reversal, the up-going flue of the pair becomes down-going, and vice-versa.

The oven does not employ direct air passages from regenerator to flues, as in the Koppers type, but provides (Figures 90 and 91) a sole

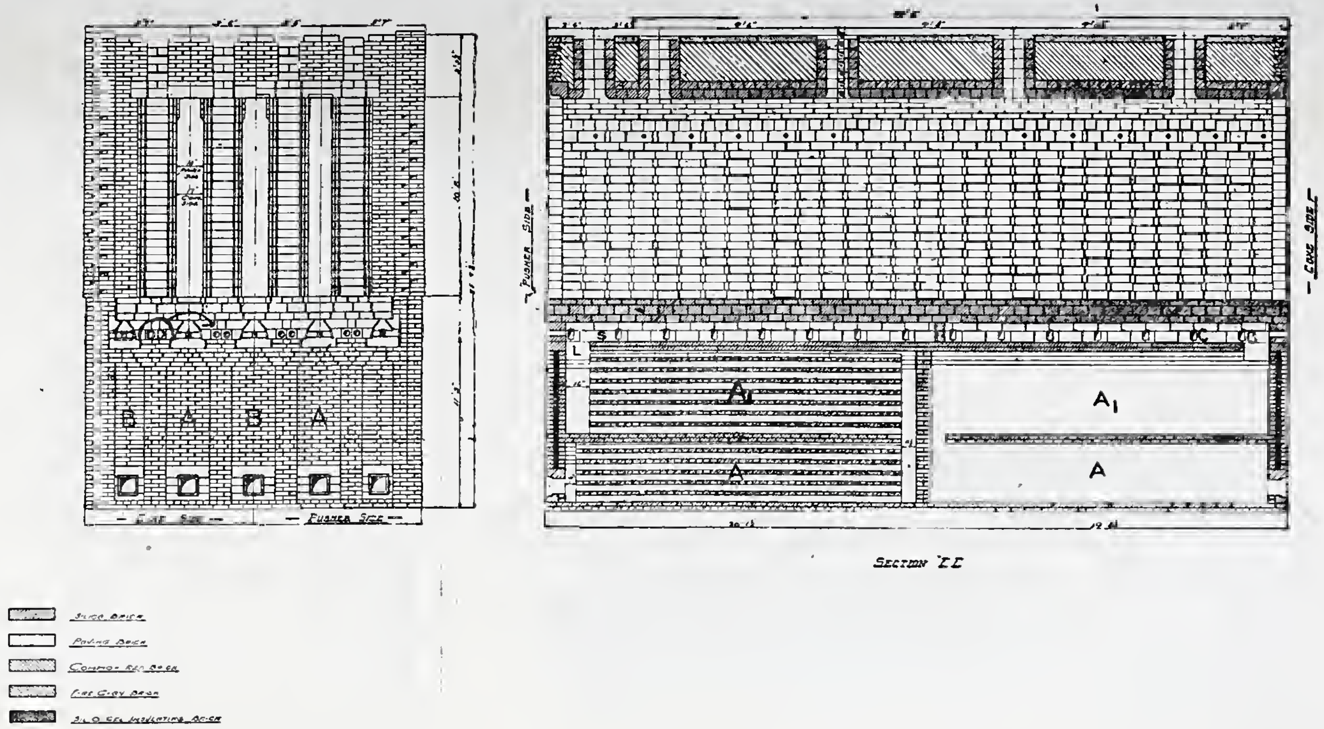


Fig. 90.—"Foundation" By-Product Coke Oven, Longitudinal Section through the Oven.

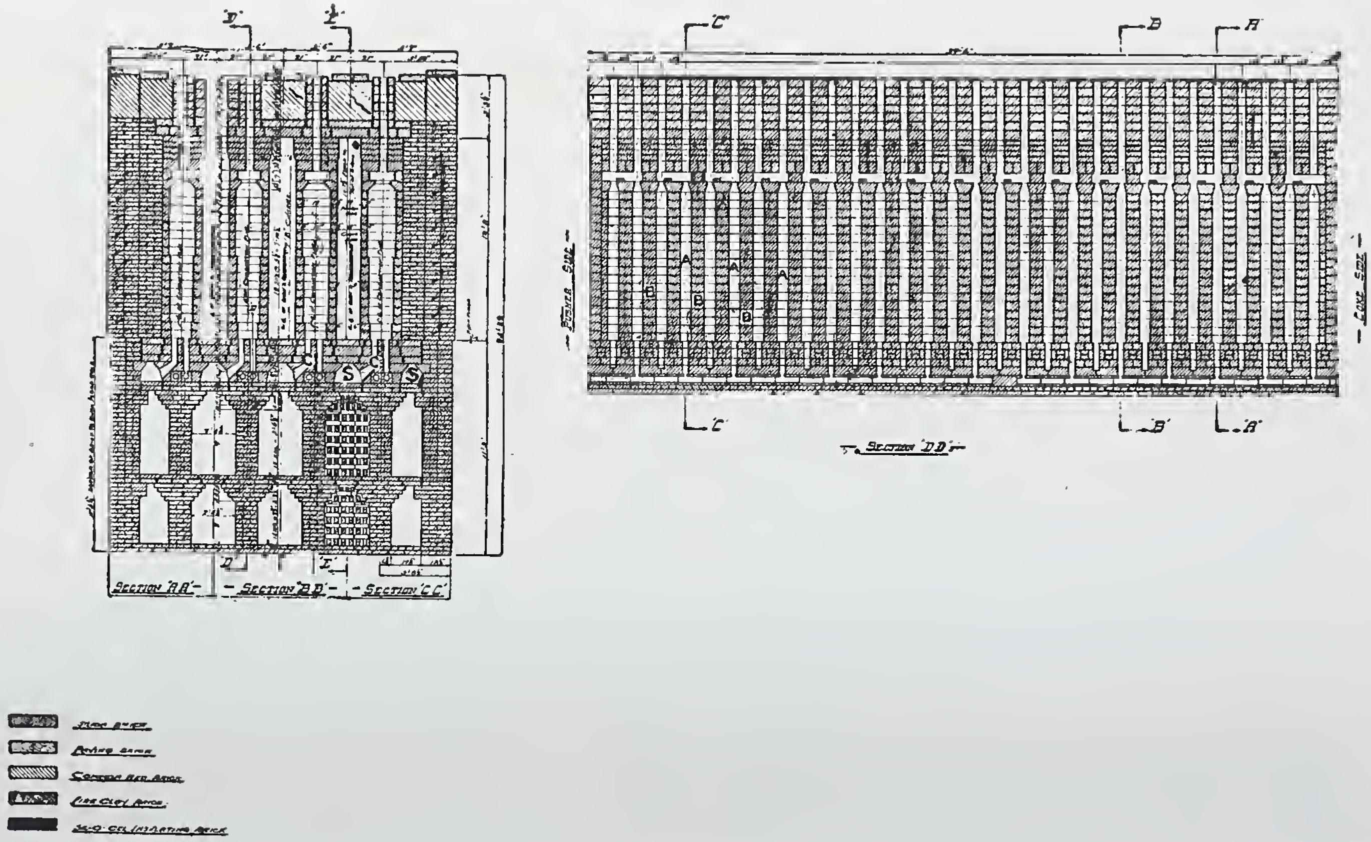


FIG. 91.—"Foundation" By-Product Coke Oven, Longitudinal Section through the Flues.

flue, or "bus" flue (s) for air, as in the Otto type and its progenitors, directly under each oven, with ports (c, c, c) into the vertical heating flues. These ports lead alternately, on right and left, to each alternate vertical flue in the row on either side. The heated air enters the sole flue from the regenerator at the outer end. Each alternate sole flue carries either pre-heated air in upward current, or in the succeeding period, after reversal, the waste gases in downward current.

Periodicity of heating, due to reversal, is local, in this type, being confined to a small area (the width of two flues). From end to end of the wall the heating may be said to be "continuous," although locally the up-burning (and slightly hotter) flame shifts its position periodically in a small area.

To make clear the course of air and gas travel through the various passages, reference may be had to Figures 90, 91, and 92. Air enters the bottom part of the regenerators A, A (on either side of the battery), traverses them longitudinally to the center wall, returns through the upper part, A_1, to the port L, and into the sole flue, S. From the sole flue the ports C, C, C, etc., lead the air diagonally upward on both sides into the bases of alternate heating flues, A, A, A, A. Here it meets fuel gas fed to the flues through nozzles of different size (increasing with the distance of each from the outer face of the battery and consequent expansion of the gas by heat). The burning gases from flues, A, A, A, A pass down flues B, B, B, B, issue through the air ports into next adjoining sole flue S_1, and finally pass through regenerators B, B, into the chimney flues F, F_1, (on either side of the battery simultaneously). On reversal, air enters regenerator B, B, and waste gases issue through A, A, the flame current being downward in flues, A, A, A, A, instead of upward as in the preceding period.

Two parallel fuel gas ducts underlie each row of heating flues, communicating with alternate flues, and one being in use, the other idle alternately. These ducts are divided near the center (at a point so placed that 16 flues are grouped on the pusher side and 14 flues on the coke side), gas being admitted at the ends. The gas ducts lie rather close, in this type of oven, to the heated sole-flues, a condition likely to cause deposition, in the ducts, of carbon from the gas. Means are provided, however (see below), for decarbonizing each gas duct by admission of air during the period that it is idle in the reversing cycle.

The regenerator compartments on the coke side of the battery are shorter than those on the pusher side, because they receive the waste gases from 14 flues as against 16 on the pusher side. The coke side regenerator, however, is larger than corresponds to a 14:16 ratio with the other side, since a somewhat greater intensity of combustion goes on in each flue of the coke side by reason of the greater oven width there.

The waste gas flues (F, F_1, Figure 92) on opposite sides of the battery, operate continuously at all times, drawing gases from alternate regenerators only, so that about half of the total waste gas is handled

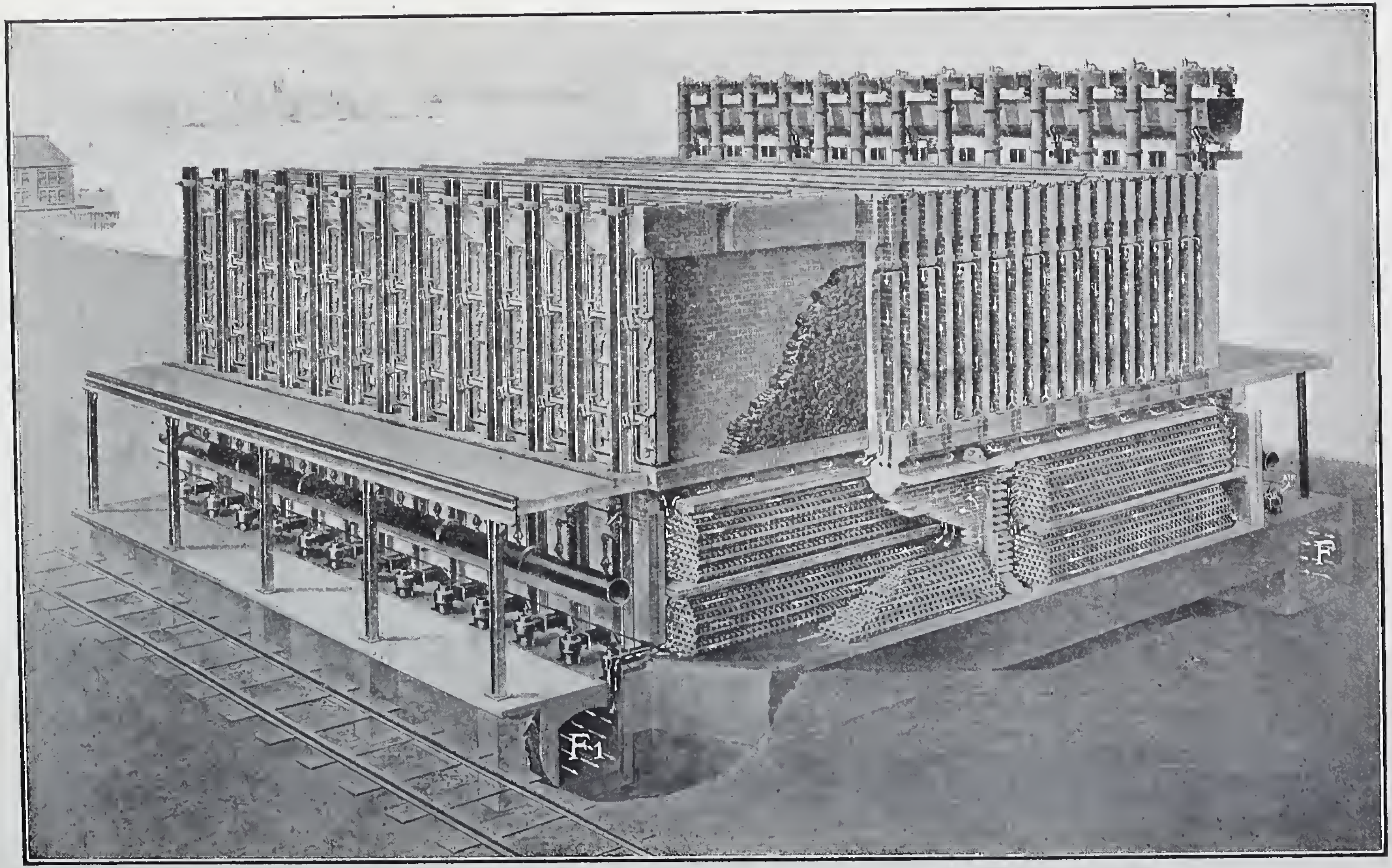


Fig. 92.—"Foundation" By-Product Coke Ovens, Perspective Sectional View of Battery.

on each side. Their size accordingly may be considerably less than in other types which use end-to-end reversal, and send all of the waste gas through one flue 50 per cent. of the time. The large reversing dampers controlling an entire battery are absent also in this type, the reversal being effected merely by opening alternate flue dampers by movement of the reversing rod, and closing of the air ports simultaneously. A separate reversing rod on the gas operates 4-way cocks which connect either the fuel gas main, or the open air to one or the other of the two gas ducts under the flues. During alternate periods an amount of air regulated by an adjustable cap on the 4-way cock is thus admitted through the ducts and nozzles to burn out carbon.

Support for the oven battery is provided by the division walls separating the individual regenerators and immediately underlying the flue walls. The flue walls themselves, as has been mentioned, gain strength from the fact that the vertical partitions between flues are practically continuous to the top of the battery, the horizontal flue of other types being done away with.

There is an undoubted advantage possessed by this type of oven, in eliminating the uneven character of the heating as between the two halves, common to those types which reverse from end-to-end of the heating wall. In this type the reversal is from one heating flue to its next adjacent flue, and any temperature fluctuation due to a difference in up-going and down-coming current, is thus localized. The fluctuation during each half-hour period, due to waning of the regenerative power in the checquers, is distributed evenly along the entire oven wall.

It is of course important in this type of heating wall, using the "hair pin" flue, that the partitions between flues remain tight so as to avoid short-circuiting of a flame and consequent under-heating in its vicinity. It is claimed that in practice such short-circuiting of flames has not caused trouble.

There has been mentioned the structural advantage secured by elimination of the horizontal flue. There should be noted also the comparative simplicity of wall structure, involving comparatively a small number of brick shapes.

A further advantage claimed for this oven is a compensating of the variation of draft along the sole flue by a counter-variation of "static pressure" in the parallel sole flue supplying air. It is set forth that the order of variation of "static" pressure (considered as absolute pressure, sub-atmospheric) in sole flue S (Figures 90-91), supplying air, is the same as that of the static pressure in the off-sole-flue S_1, and that the gradation of pull along the down-coming sole flue balances the gradation of motive pressure in the up-going sole flue. If this holds true, the effect as regards relative flow of gases in the flues is compensatory, and no necessity exists for graduation of the air ports (or draft ports) for this purpose from end to center of the oven. Whether in actual operation of the oven such compensation has been established, is not at this writing known. A record of relative static pressures at the tops of the various flues has been made on ovens in operation and practically inconsiderable variation found. It appears, however, that such measurements are hardly sufficient in themselves to indicate relative flow of gases in the flues. The air ports in this oven are, as a matter of fact, graduated in some degree from end-to-end of the oven to take care of variation in heat requirement due to taper of the oven width.

Access flues extending to the top of the battery afford a means of correction of leaky or stopped nozzles, while peep holes at the ends of the sole flues are chiefly relied upon for inspection of temperature conditions in the vertical flues, any irregularity being noticeable at the respective port into the off-sole-flue.

The checquer filling of the regenerators is of standard 9-inch brick, and is laid in such manner, for longitudinal passage of the gases, that a smaller drop in pressure occurs than with staggered checquers in other types.

The "Gas Machinery" Regenerative Coke Oven.

The principle of the "hair-pin" flue, localizing the reversal of heating flames in adjacent flues, is made use of in the design of the Gas Machinery Oven, and is prior there to its application in the Foundation oven just described. In this oven (see Figures 93-96), the hair-pin is inverted and the direction of the heating flame is first downward, the fuel gas being introduced from the top. Preheated air enters the sole flue (E), Figure 93, at one end, this flue underlying the entire oven length, and thus constituting a "bus flue" of unusual length to distribute air to the vertical heating flues. Air passes up the vertical channels G, G (Figure 94), intermediate to the U-shaped heating flues, meets fuel gas at the top, J, J, and forms flames which burn downward in K, K, then upward in L, L. The waste gases finally pass downward through the channels (P, P,) into the next adjoining sole flue, S, these channels P, P, and sole flue S, becoming, after reversal, the up-going air flues.

The regenerators are individual to each oven, and consist each of one long chamber underlying the entire oven. Each regenerator alternates by half-hour periods for air and waste gas. Adjoining regenerators accordingly are operating always in opposite direction. Reversal takes place at the end of the battery, where the two waste gas flues meet, the reversing valve connecting them alternately to chimney and to air supply. Reversal of fuel gas is made on top of the battery (see Figure 96), there being two supply lines over each row of flues, connecting to alternate flues, one line being in use, the other idle alternately.

It is claimed for this oven that it secures cooler tops than those types having a large horizontal flue; that it affords easy adjustment of gas to each flue, and that, in common with the Foundation oven above

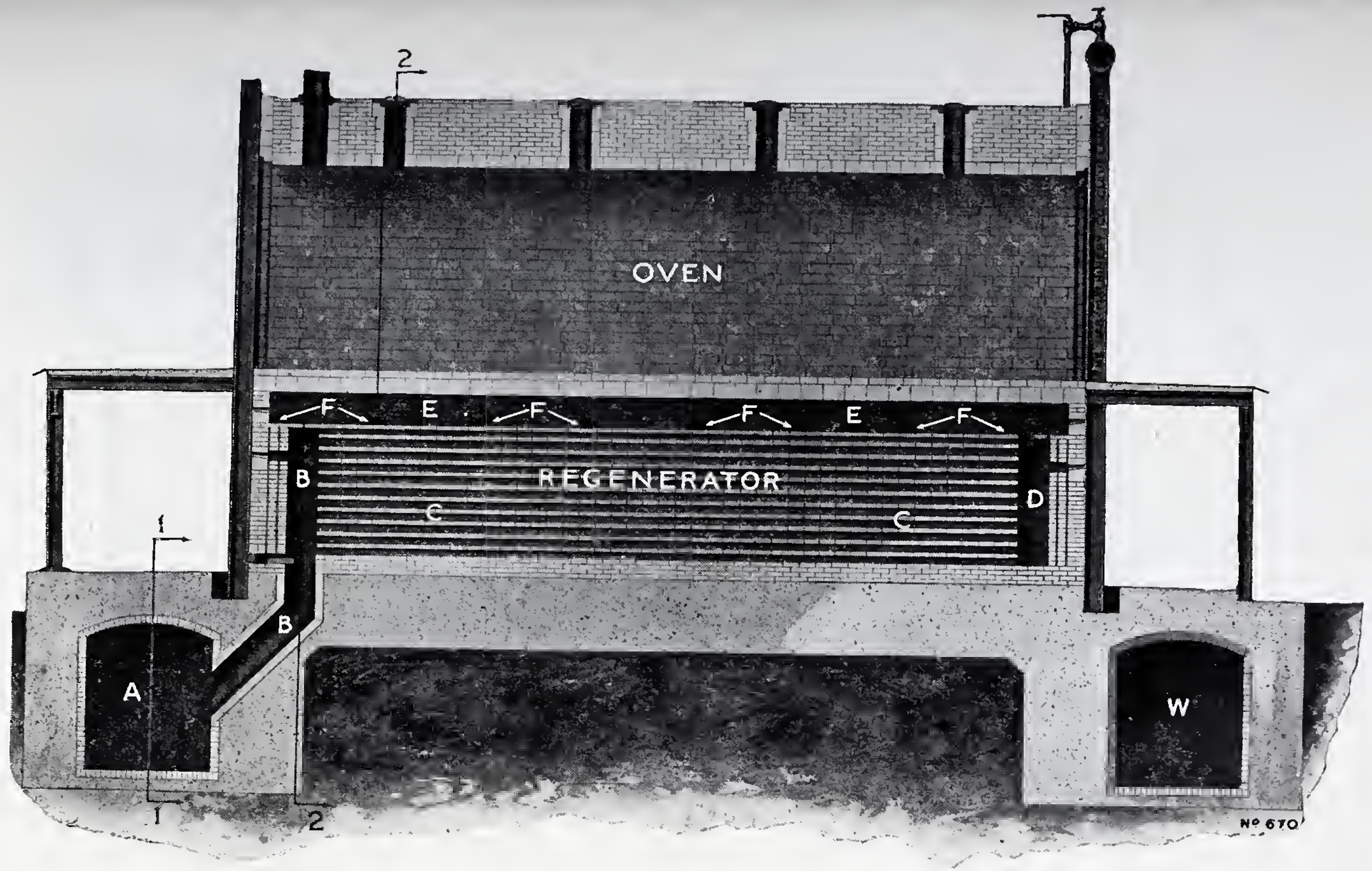


FIG. 93.—"Gas Machinery" By-Product Coke Oven, Longitudinal Section through the Oven.

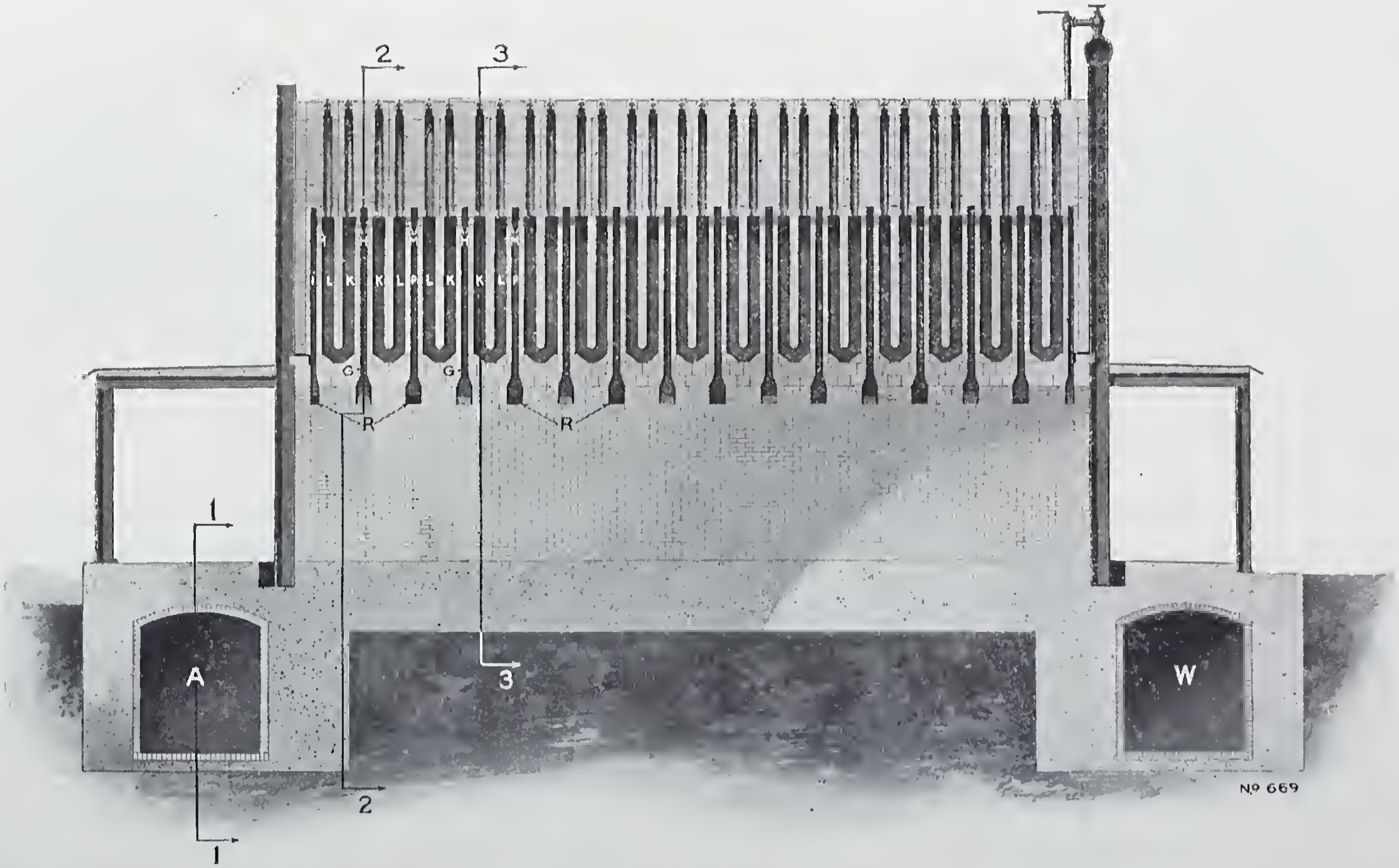


FIG. 94.—"Gas Machinery" By-Product Coke Oven, Longitudinal Section through the Flues.

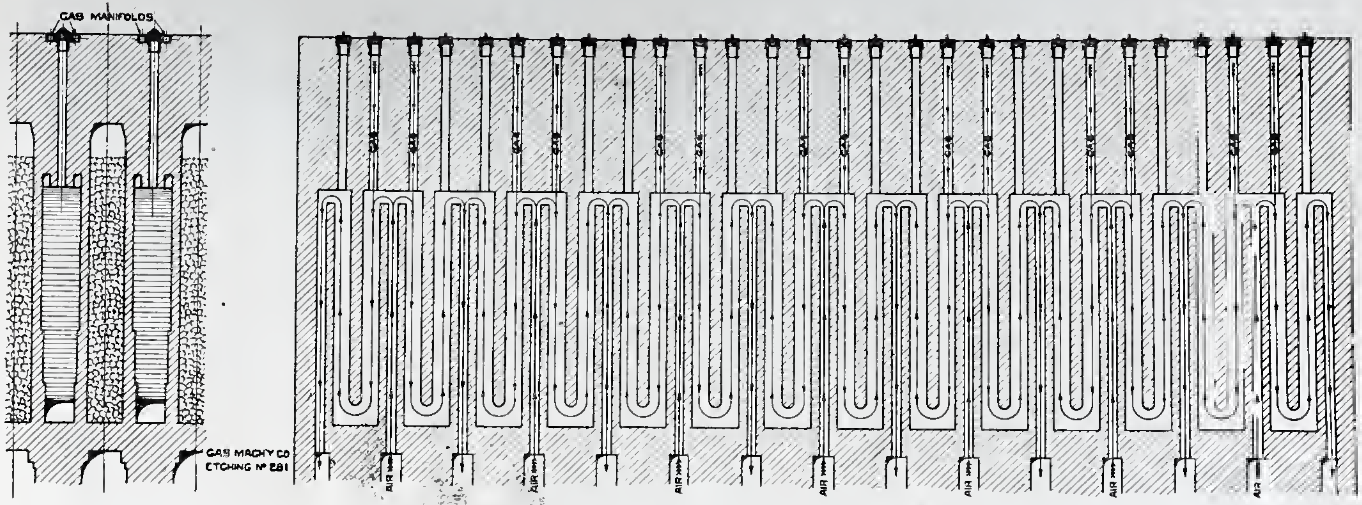


Fig. 95.—"Gas Machinery" By-Product Coke Oven, Section Showing Course of Air and Gas Travel through the Flues.

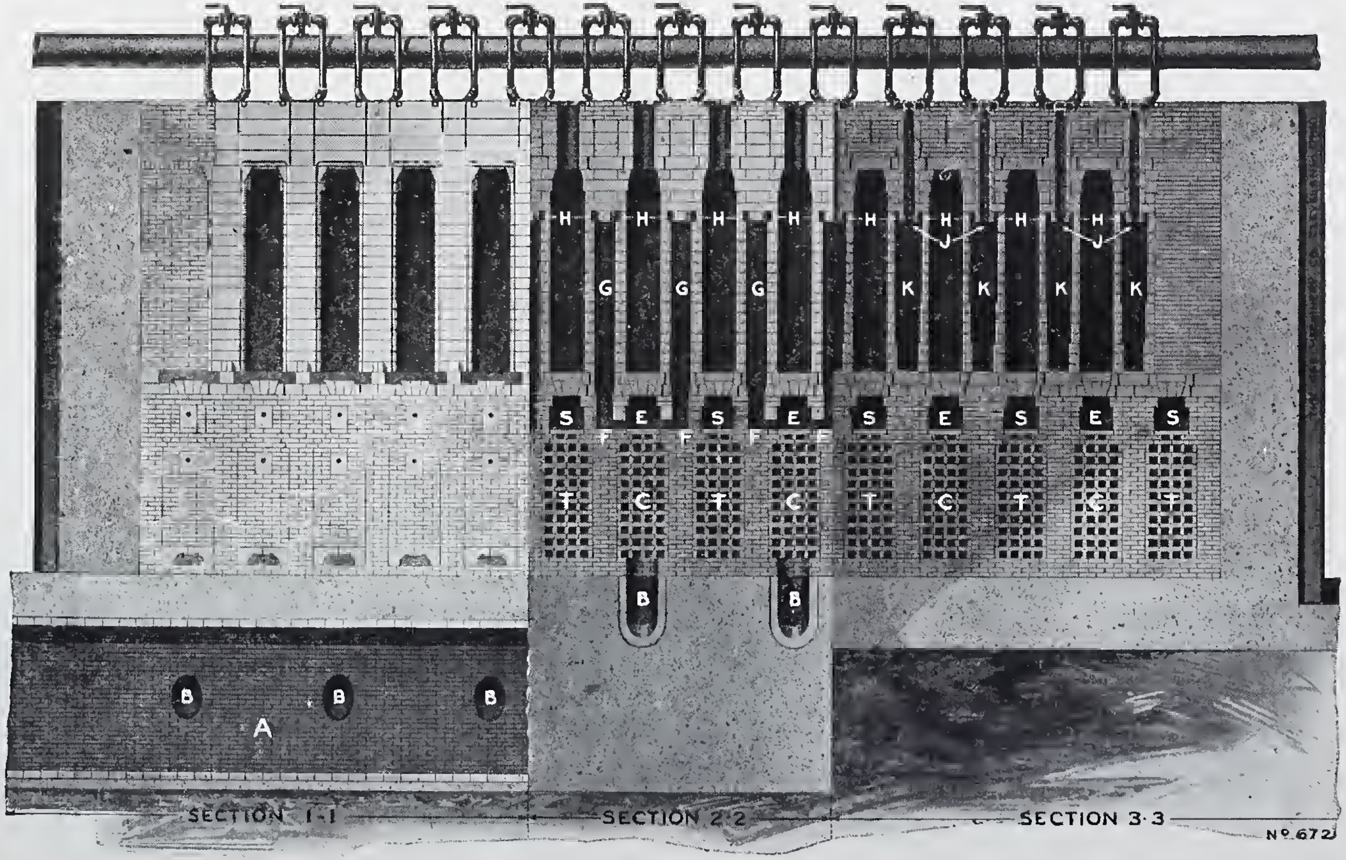


FIG. 96.—"Gas Machinery" By-Product Coke Ovens, Transverse Section of Ovens, or Lengthwise of Oven Battery.

described, it avoids the manifest drawbacks of end-to-end reversal of heating gases in the wall.

The Roberts "Flueless" By-Product Coke Oven.

The Roberts oven, promoted by the American Coke & Chemical Co., Chicago, Ill., has been built, during the period 1914-1923, in three commercial installations in the United States. Only the most recent one of these has been continued in successful operation. During the World War, this oven was represented to U. S. Governmental authorities as exclusively the type of by-product oven applicable to the coking of Interior Province coals, such coals as those abundantly available in Illinois and neighboring States, and regarded, on account of their high oxygen and sulphur content, as not adapted in general to the commercial production of coke. These claims commanded attention at the time, owing to the war emergency and the need for wider fields of coal supply to coke and by-product producers.

An official investigation therefore of the performance of the Roberts oven was made in the year 1918, by the Bureau of Standards and Bureau of Mines, acting under instructions from the President. A 15-day test[14] was carried out on a plant of 24 Roberts ovens, at Canal Dover, Ohio, using a mixture of Franklin Co., Illinois, and Pike Co., Indiana, coals. Coke was produced which the Governmental authorities pronounced of fair quality for metallurgical use, and the yield of by-products per ton was good.[15] The coking capacity of the ovens, however, proved to be only 14 tons of coal per day, or 70 per cent. of their rated capacity, and the entire yield of gas was used in the heating flues. The efficiency of the ovens was therefore low.

A further demonstration was undertaken later, in the year 1918, under the same Government auspices, but was discontinued before completion and indefinitely postponed.

The Government tests on the coking of Illinois-Indiana coals in the Roberts and in the Koppers oven, appear to leave unsubstantiated the claims that there are elements of design in the Roberts oven rendering it peculiarly and exclusively adaptable to the coking of these coals. The use of Illinois coals in by-product coke ovens is largely a matter of economic balance between accessibility and cost of coal on the one hand, and the required blast furnace performance and coke quality on the other. The quality of coke made in a by-product oven, although affected in some measure by the coking rate, that is, by the temperatures used and width of oven, is concerned more with operating conditions and oven dimensions than it is with the type of coke oven used. (Bulle-

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[14] Miscellaneous Publication 46, U. S. Bureau of Standards.

[15] For purposes of comparison, a similar test was later made by the same Governmental authorities on a Koppers oven plant, using one of the same coals. Equally good results in coke and by-products were obtained. See Technologic Paper 137, Bureau of Standards, 1919.

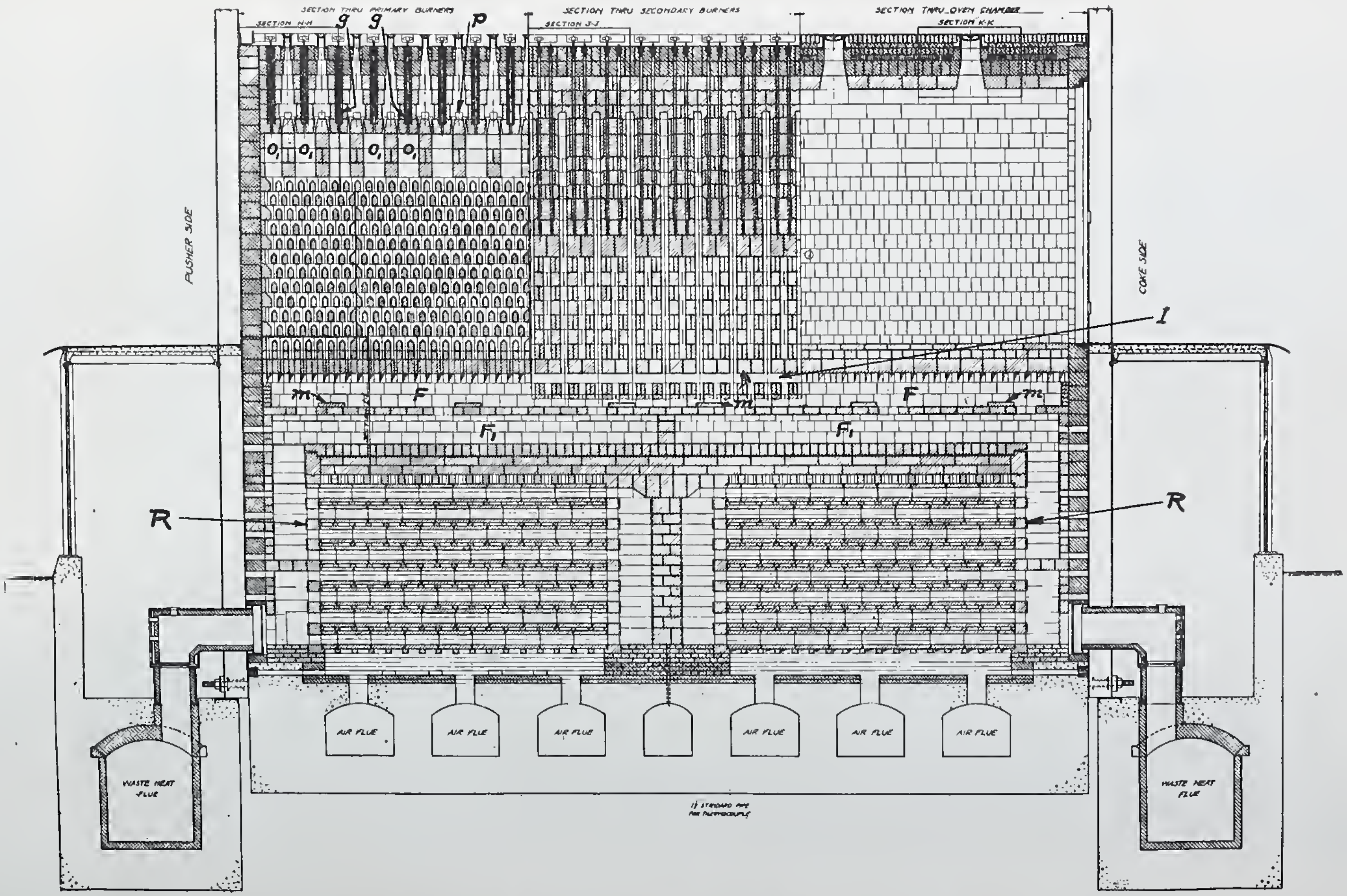

FIG. 97.—Roberts "Flueless" By-Product Coke Oven, Longitudinal Section in Chequered Heating Wall, and in Oven.

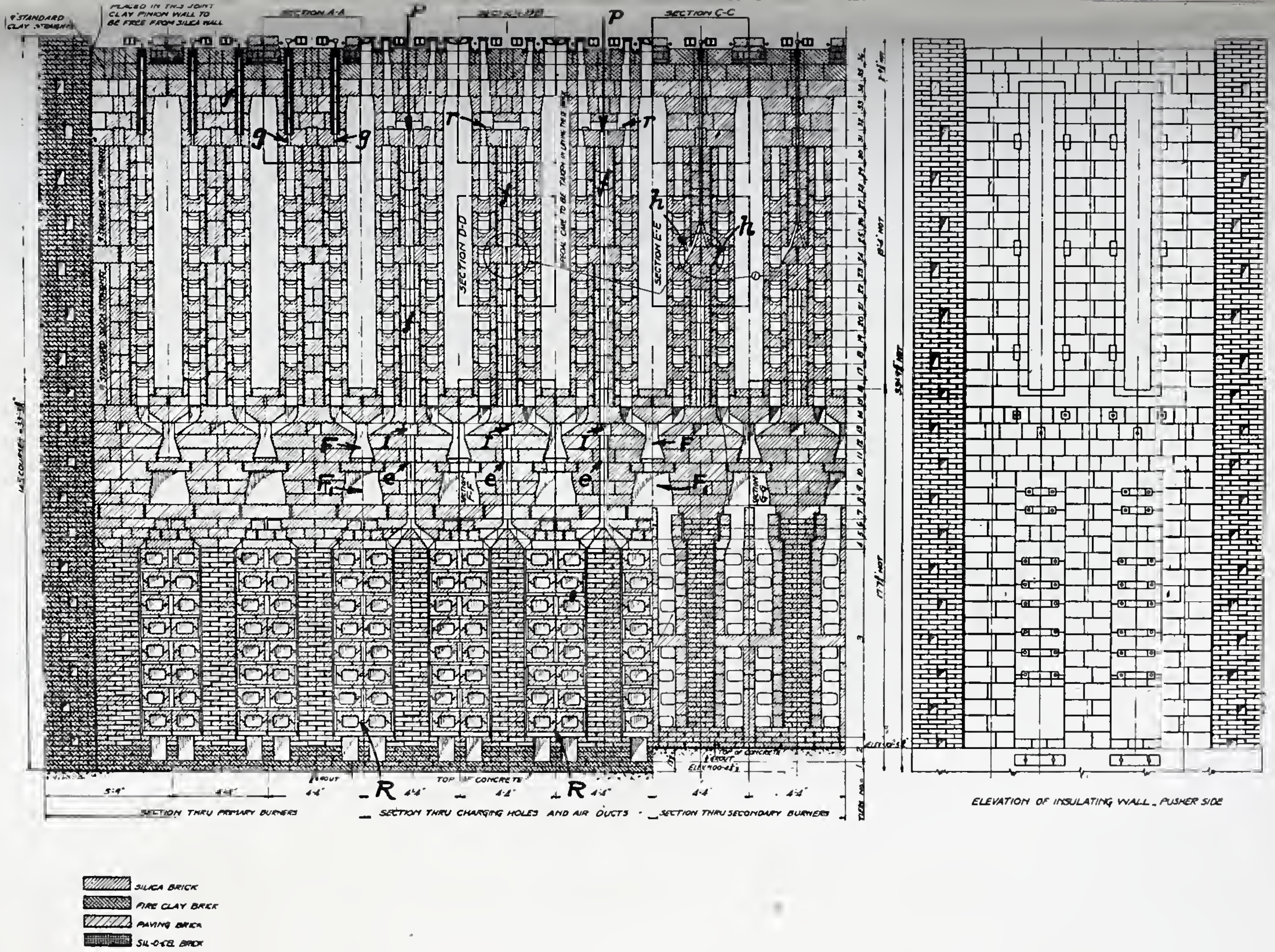
9" STANDARD CLAY STRAIGHT
PLACED IN THIS JOINT CLAY PINION WALL TO BE FREE FROM SILICA WALL
SECTION A-A
SECTION B-B
SECTION C-C
SECTION D-D
SECTION E-E
SECTION F-F
SECTION G-G
P
P
g
g
r
r
f
h
h
F
F
F₁
F₁
I
I
e
e
e
R
R
SPECIAL CARE TO BE TAKEN IN LAYING THIS WALL
TOP OF CONCRETE
SECTION THRU PRIMARY BURNERS
SECTION THRU CHARGING HOLES AND AIR DUCTS
SECTION THRU SECONDARY BURNERS
5'-9"
4'-4"
4'-4"
4'-4"
4'-4"
4'-4"
4'-4"
ELEVATION OF INSULATING WALL - PUSHER SIDE
SILICA BRICK
FIRE CLAY BRICK
PAVING BRICK
SIL-O-CEL BRICK

FIG. 98.—Roberts "Flueless" By-Product Coke Ovens, Section Transverse to Ovens.

tin 138, Bureau of Mines, The Coking of Illinois Coals, by F. K. Ovitz, 1917, is an excellent summary of progress in this field.)

A new plant of the Roberts type, 80 ovens in two batteries, owned by the St. Louis Coke & Iron Co., was put into operation in January, 1921, at Granite City, Illinois. This plant, operating mainly on a mixture of Illinois and Indiana coals, is producing good coke for blast furnace use.

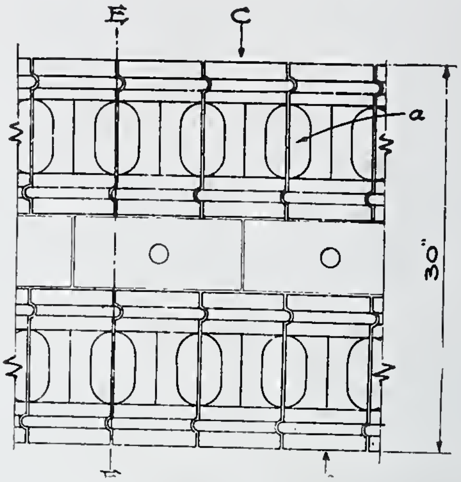

Fig. 99.—Roberts Ovens, Detail of Brick in Heating Walls, Plan.

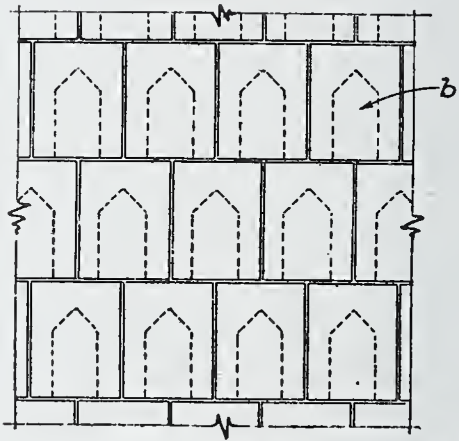

Fig. 100.—Roberts Ovens, Detail of Brick in Heating Wall, Vertical Section.

One battery at this plant is operated[16] especially for blast furnace coke, on 90-95 per cent Illinois coal (Franklin, Jefferson, or Williamson County) with 5 to 10 per cent. Pocahontas (Virginia). The addition of the last-named small percentage of low-volatile Eastern coal is re-

[16] From information furnished the author by M. D. Curran, General Supt. St. Louis Coke & Iron Co., Granite City, Ill., under date of Feb. 27, 1924.

sorted to, in order to strengthen the coke, and to make it suitable for the faster driving of the blast furnace here desired for making basic iron. It has been found possible at this plant to use 100 per cent. Illinois (counties above named) or Indiana ("Ayrshire") coal, and make therefrom blast furnace coke well suited to such furnace operation as sometimes required. As a general rule, however, the Pocahontas coal is added. The second battery is operated for production of domestic, foundry or water-gas coke and the coal mixture is varied to suit the purpose for which the coke is intended.

Description of the Roberts Oven.—The essential distinguishing element of design in the Roberts by-product coke oven, rendering it unique among existing oven types, is the "flue-less" heating wall made up of staggered checquer brick, with interconnected, multi-baffled passages between the checquers for the heating flames. There are no separate flues, except that in the upper part of the wall (at O_1, Figure 97), for about 1/5 of its height, separate passages or flues, 24 in each wall, direct the flames downward to the checquers. In the usual (recuperative) type, gas and preheated air enter these passages at the top and burn downward throughout the entire wall. There is no reversal of current. On reaching the checquered structure, the flame for each of the 24 flues is divided into three parts, which then pass in irregular course downward through the checquers, as directed by the relative amount of draft from below.

Each oven is provided with independent heating walls, two ovens thus being separated by two heating walls, with intermediate division wall, in which are the air flues, 24 in number, leading upward from the recuperators below, (see Figures 98 and 103). The aggregate thickness of the brick structure between two ovens, wall to wall, is 30 inches. The mass of brick in this wall structure is claimed to be more than twice as great as that in the average of vertical-flued ovens, affording thus a greater reservoir of heat to assist in the coking process.

The key to the Roberts heating wall structure lies in the principal brick shape, C (Figure 99). These bricks laid side by side, extend the full width of heating wall (12½ inches), but in the central portion each is constricted in width and height so as to leave passages, a (Figure 99), and b (Figure 100), vertical and horizontal. Successive courses are laid in such manner as to stagger the vertical passages. The convoluted outline of these heating-wall brick can best be seen in the perspective illustration, Figure 101. The shape of the constricted portion is such that a partition wall of non-uniform thickness is formed between the combustion space and oven chamber, this wall in certain sections (somewhat less than 20 per cent. of its area) being as thin as 3¼ inches. The average thickness for direct transmission of heat, although difficult to compute with accuracy, is no doubt less than that in the flue-type ovens. The Roberts heating wall has also a somewhat greater area for direct transmission of heat than have most of the flue-type ovens.

It is largely upon these features of the heating wall construction that the Roberts claims for superiority are based in respect to the coking of the Illinois type of coal. If, by reason of a lesser thickness of brick to be penetrated by heat, and an equal or greater wall area subject to direct transmission of heat, the Roberts oven wall, compared to other types, conducts a greater amount of heat to the coking mass in a given time, such a condition should tend toward a more rapid

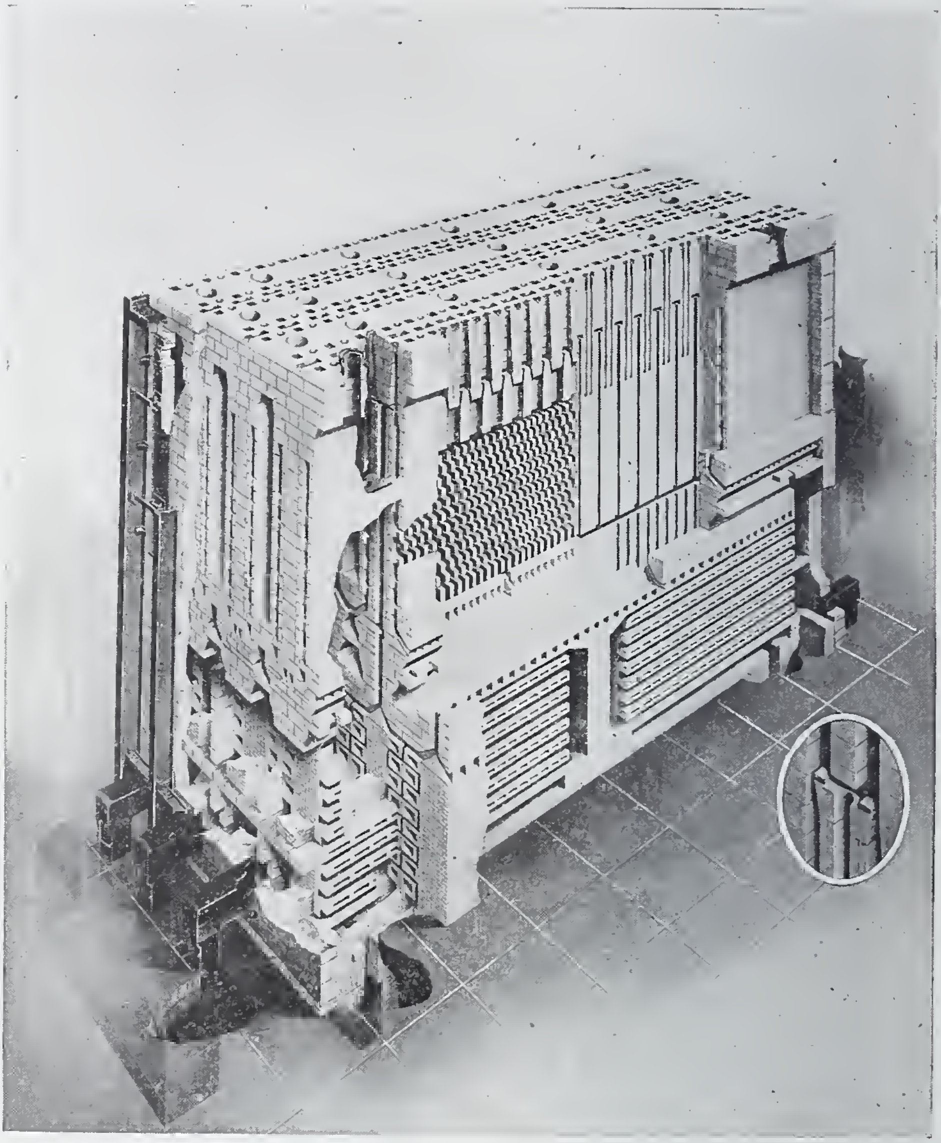

Fig. 103.—Roberts By-Product Coke Ovens, Perspective Sectional View of Oven Battery (detail of top of air-flue in insert).

rate of coking, with an equal temperature differential; or in the same sense, an equal rate of coking with lower temperature differential.

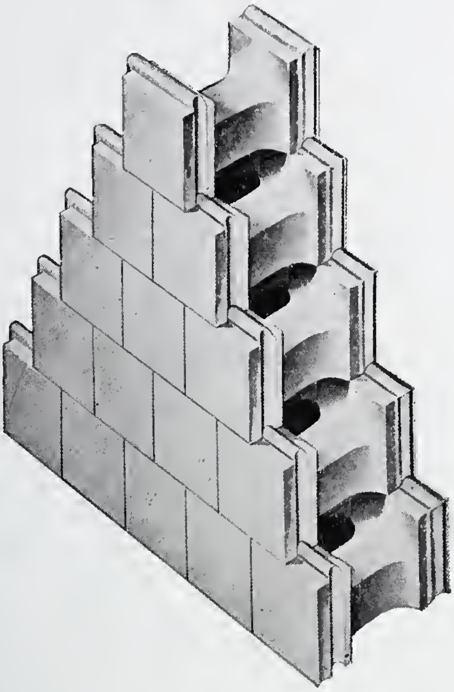

Fig. 101.—Roberts Ovens, Detail of Brick in Heating Wall, Perspective.

Coal of the Illinois type has in general been found to yield an improved quality of coke under these conditions, that is, when temperatures lower than common in the coking of high grade coals are used.

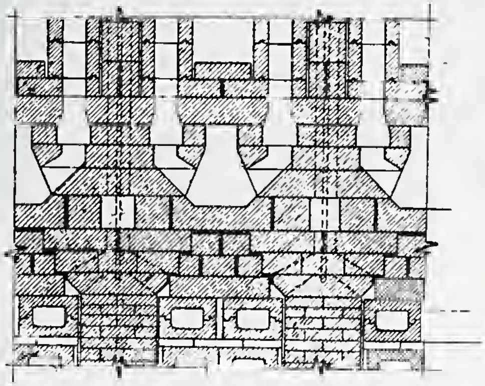

Fig. 102.—Roberts Ovens, Transverse Section showing Detail of Brick at Base of Ovens and Flues.

Whether such superiority in rate of heat transmission actually exists is a matter on which records giving complete test data are not available.

It is to be noted in this connection that the resistance of the coke or carbonizing mass itself to heat transmission, is a factor of great importance affecting the rate (see p. 249), and that when coking has progressed inward a short distance from the oven wall, there may be a greater resistance to heat transfer interposed by the coked mass than exists in the wall itself. This factor is common to all ovens.

Reports from the Roberts plant at Granite City, Illinois, indicate that Illinois coal is being coked there at a rate (in inches of oven width per hour) approximately equal to that attained in the flue type oven using similar coal. Whether oven wall temperatures are less in the Roberts plant for attaining these results is not definitely known. The lesser width of oven should in itself make for such a condition, owing to the principle, explained in an earlier chapter (pp. 135-7), that during the coking period, the rate grows slower as the coking zone progresses toward the center of the charge and farther from the source of heat.

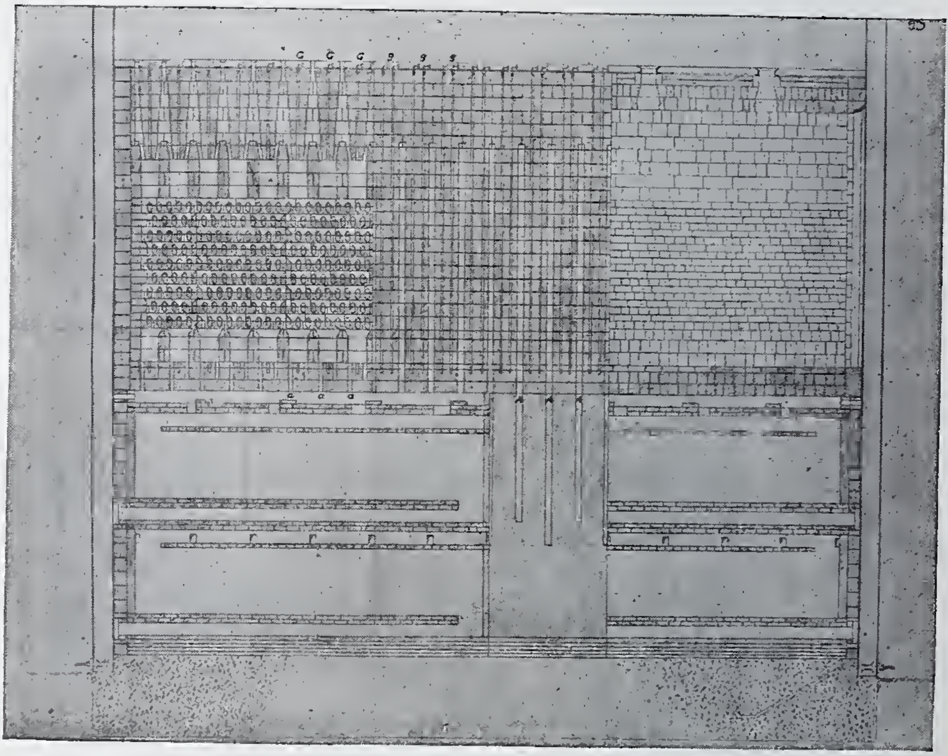

Fig. 104.—Proposed Regenerative Type of Roberts By-Product Coke Oven, Longitudinal Section (A, A, A, and a, a, a, indicate air flues and inlets,—G, G, G, and g, g, g, fuel gas inlets).

Outline of the Roberts Heating System. (For detailed description of the Roberts heating system, see "Design and Operation of Roberts Coke Oven," by M. W. Ditto, presented to American Institute of Mining and Metallurgical Engineers, March, 1923).

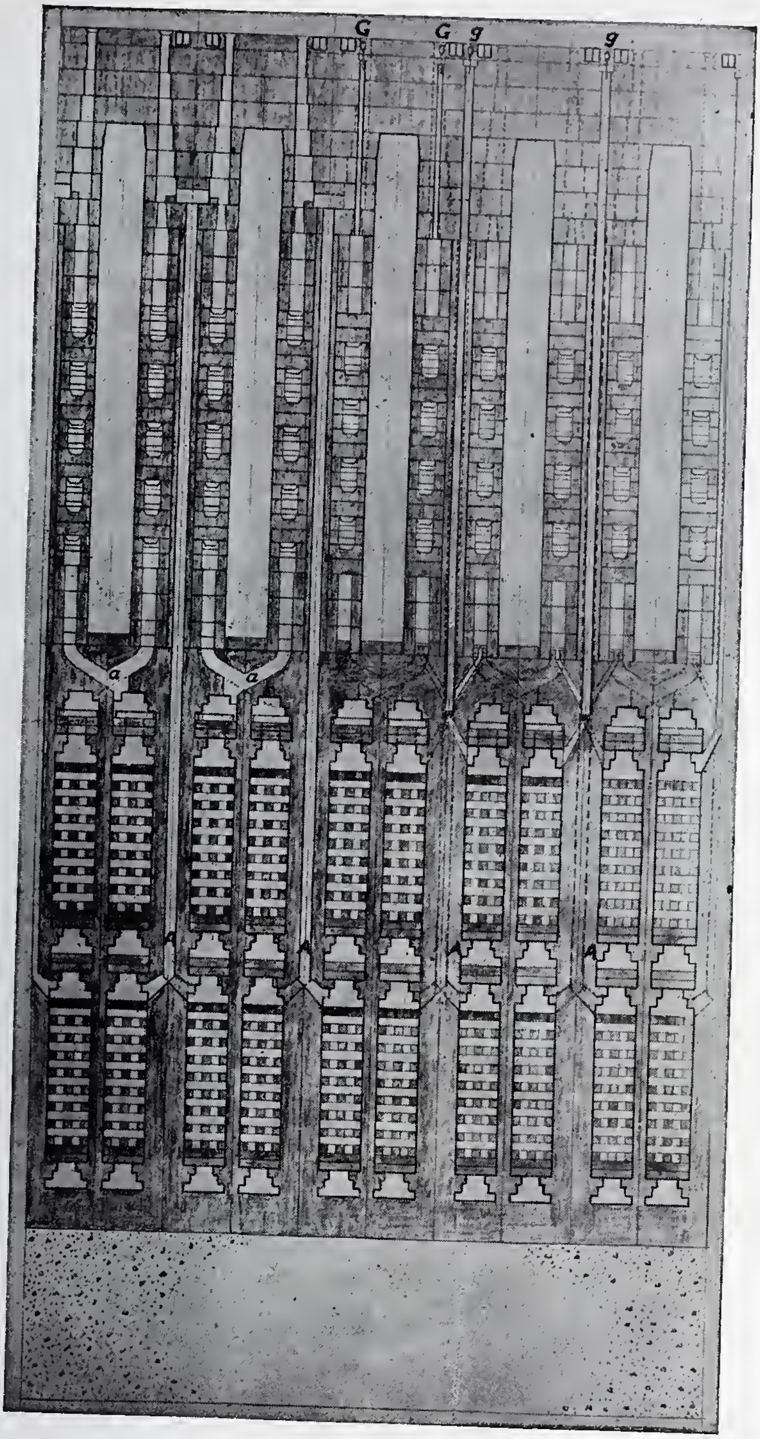

Fig. 105.—Proposed Regenerative Type of Roberts By-Product Coke Ovens, Transverse Section (showing upper and lower double tiers of regenerators to be used when both air and producer gas are preheated).

Although a *regenerative Roberts oven* has been designed (see Figures 104-105), it has not, at this writing, been put in operation. The following description of the Roberts system refers therefore to the usual (recuperative) type.

There is no periodic reversal of flow of air and waste gases, the recovery of waste heat being recuperative, not regenerative. The heating flames pass continuously *downward.* Preheated air passes *upward* in ducts in the division wall between the heating walls. The air leaves the recuperators through 48 short vertical ducts (e, e, Figure 98), entering a horizontal equalizing chamber (1) at the base of the division wall, from which 24 vertical flues (f, f) conduct it upwards in the division wall to a point (p, Figure 98) 20 inches below the level of the oven tops. Here it is diverted to either side, and with sliding brick damper control (r, Figure 98), is drawn downward in the heating wall at 24 points with the primary fuel gas, admitted at the burners, g, g. The full requirement of air enters here at the primary burners. Half of the total requirement of gas is admitted here, and the remaining half at h, h, the secondary burners, 70 inches below the primary, or 7½ feet below the oven top. Gas supply ducts to the secondary burners lie in the division wall. They are of 1 inch diameter, and when constricted by stoppage of deposited carbon, can, it is claimed, be readily cleaned from above, or at regular intervals burned out with air.

The waste gases from both heating walls are drawn into a common sole flue (F), under the oven, by a row of 72 short diagonal ducts at the base of each heating wall. Under the influence of the chimney draft they pass downward from this sole flue through six ports (m, m, Figure 97), provided with sliding brick dampers into a sub-sole or "bus" flue F_1 divided in the middle, and are drawn from the outer end of this into the recuperators.

It is to be noted that the Roberts oven in common with the Otto-Hoffman and certain other types, applies the draft at one end of a horizontal bus flue, in which the degree of suction must vary from end to end. Whether the flames in a checquered wall, unguided by separate flues, and seeking the paths of least resistance, will be so influenced by the inequalities of draft that they produce heating more uniform or less uniform than in the flue-type of heating wall, can only be determined by the results of extended trial. The baffling and impingement effect of the studding brick of the Roberts wall is claimed to promote rapid and complete mixing of the gases and to insure thus great uniformity of heating.

It appears that the Roberts system affords a ready control of the fuel gas and its distribution in the wall, through its large number of points of admission. It must be assumed in this connection that carbonizing troubles in the supply ducts can be held to a practical minimum. The individual air supply dampers (r, r, Figure 98) are also readily accessible. Claims are made for unusual strength in the oven wall due to the interlocking and keyed structure of the wall brick.

The Roberts recuperator (R, Figures 97-98, also Figure 103) is built of silica tiling arranged for longitudinal flow of the hot waste gas in two passes, and transverse flow of air in 8 passes. In spite of the high expansion coefficient of the silica material, it is claimed that this recuperator remains tight under the strain of the varying temperature conditions in its different sections.

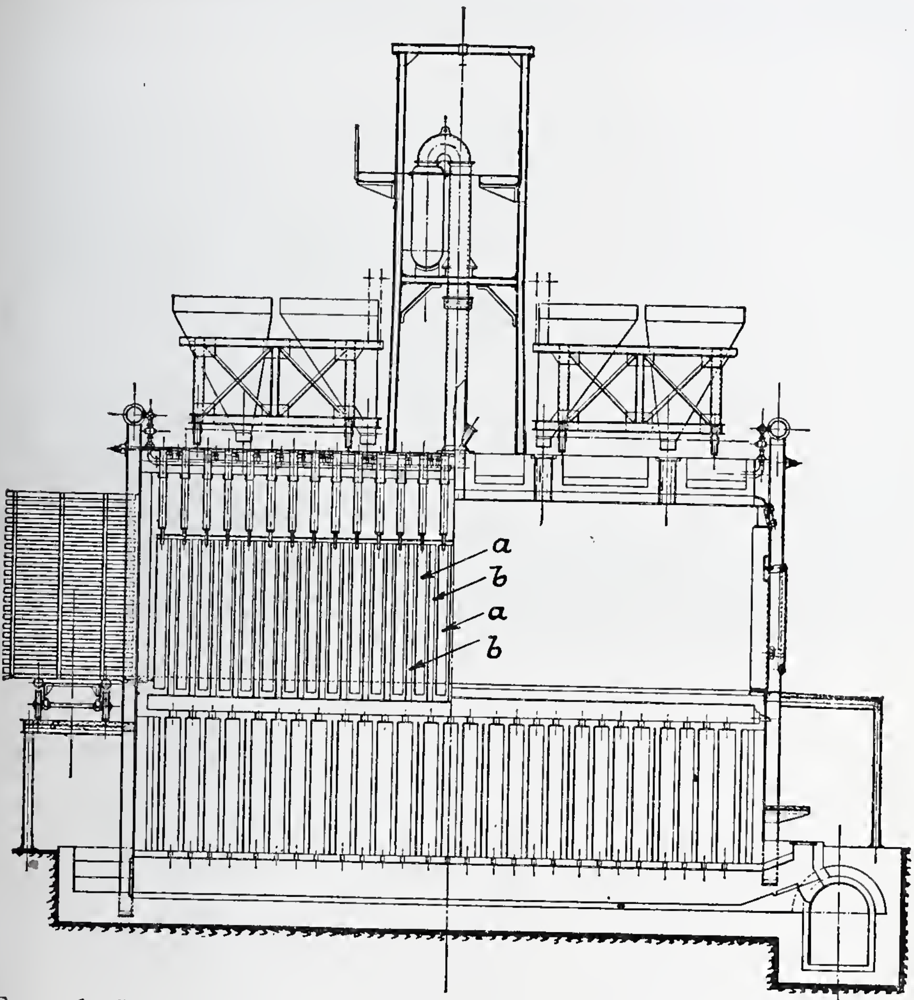

FIG. 106.—Piron Recuperative By-Product Coke Oven, Longitudinal Section.

The Piron Recuperative By-Product Coke Oven.

A late acquisition to the list of by-product oven types used in America is the Piron, developed originally in Russia, by Emil Piron, one time associate of Coppee, the Belgian pioneer.[17] An experimental installation of twelve of these ovens was built at the plant of the Woodward Iron Co., Woodward, Ala., but at the time of this writing had been dismantled and had not had sufficient trial to demonstrate fully its success.

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[17] This oven is promoted in America by Piron Coal Distillation Systems, Inc., 43 Broad St., New York.

The Piron oven burns gas downward in vertical flues (a, a) in the heating wall, with preheated air drawn upward in vertical ducts (b, b) between the combustion flues (see Figures 106 and 107). The flames burn entirely in the one direction.[18] A distinctive feature of this type is the simplicity of temperature control. No gas nozzles or valves for the individual burners are used. It is claimed that gas and air supply at each burner is induced in the right quantity by the downward draft and flame travel, and that an automatic equalization of temperatures occurs, lower temperatures inducing more gas and higher temperatures retarding gas until a balance is established.

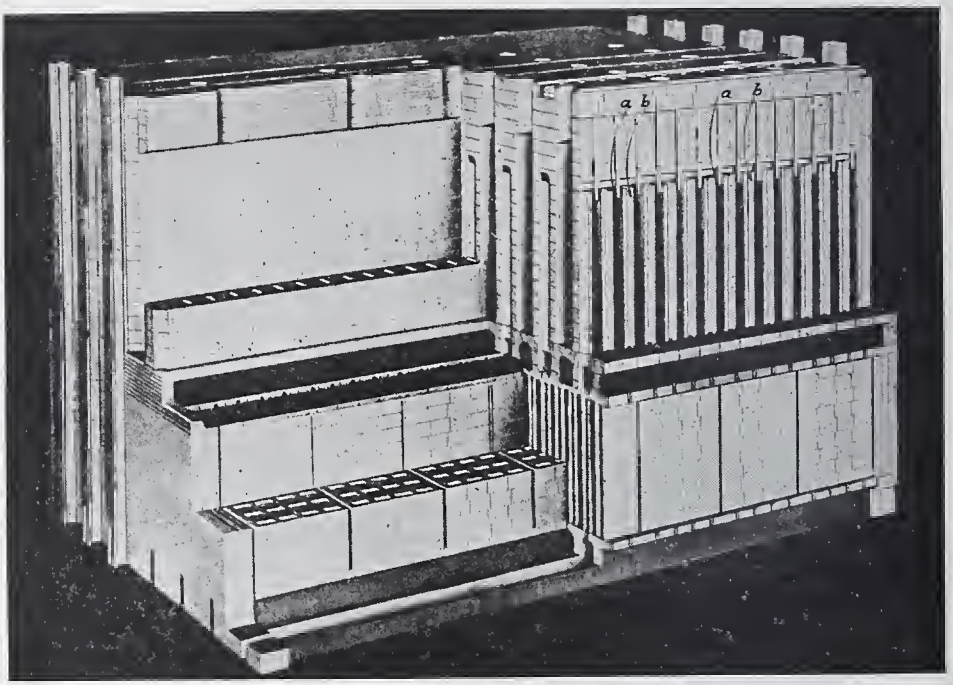

FIG. 107.—Piron Recuperative By-Product Coke Ovens, Perspective Sectional View of Oven Battery.

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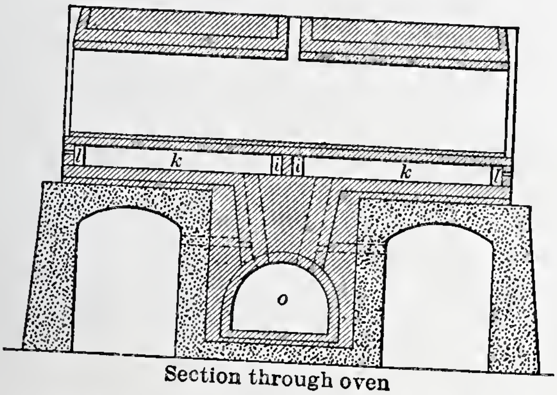
[18] The principle of the downward-burning flue as compared to the upward-burning, is thus stated by the inventor: "When gas is admitted in the bottom . . . and the flame burns upwards, the draft is naturally stronger where the vertical flues are hotter. As a stronger draft increases the combustion, these flues have a tendency to grow hotter, and it is necessary to admit the gas through small orifices offering a noticeable resistance to avoid over-heating of such flues. With downward combustion it is quite different because when the flues are hotter the downward draft is smaller and the intensity of the combustion decreases without need of any means of regulation."—See article by Emil Piron, "By-Product Ovens at Woodward, Ala.," *Gas Age*, 47, 83-85 (Feb. 10, 1921).

Adjustment of stack draft and of inlet air for each oven as a whole is said to provide adequate regulation.

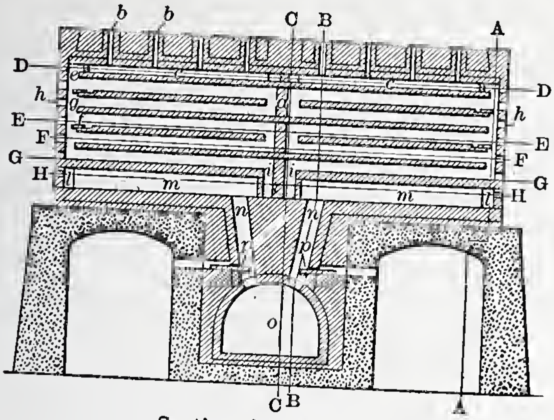
Whether such automatic regulation in the heating wall proves effective in actual practice, remains to be demonstrated.

The Rothberg By-Product Coke Oven.

The Rothberg oven, a horizontal-flued type, was built at two plants, during the early days of by-product coking in the United States, viz., for the Lackawanna Steel Co., Buffalo, N. Y. (282 ovens), and the Cleveland Furnace Co., Cleveland, Ohio (80 ovens). The latter installation was rebuilt in 1910, the Rothberg ovens being replaced by Semet-Solvay.



Section through oven



Section through flue

FIG. 108.—Rothberg By-Product Coke Oven.

The Rothberg oven (Figure 108) is heated by half-length horizontal flues, five high, each tier of flues flanking an oven on either side. The solid division wall of the Semet-Solvay battery, separating the ovens, is absent, but each flue wall is strengthened by a solid transverse partition wall at its center. The flames pass continuously in a downward course, air being introduced at the top, preheated by two horizontal passes along a recuperator flue above the top-most combustion flue. Gas is introduced successively at the ends of the horizontal flues. The waste gases pass through a sole flue under the oven, then by a dampered outlet to the chimney flue and through waste heat boilers.

It is claimed that the costs both of construction and operation of this oven are unusually low.

The Klönne, or National Chamber Oven.

There are two installation of this oven in the United States, one at Muncie, Ind. (22 ovens), and one at Seattle, Wash. (20 ovens), built primarily for the manufacture of city gas. The oven is a horizontal chamber, 27 feet long, 8 feet high, 15½ to 18 inches wide, and is arranged in groups or settings of 4 or 5 chambers each. These are heated by producer gas from generators (two to each setting) placed immediately in front of the ovens. Between every two ovens is a single row of vertical heating flues connecting horizontal chambers at top and bottom, in which are provided sliding dampers to regulate the distribution of heat. The air is preheated in recuperators directly under the flue-walls, and the waste gas passes also through boilers, between the recuperators and the chimney flue, thus supplying steam to the producers.

The Summers Coke Oven.

The Summers oven,[19] which has been operated experimentally in a small way, near Harrisburg, Illinois, is a continuous horizontal coking device. The design of this oven is unique in providing for continuous feed of coal and for compression of the carbonizing mass during the progress of the coking, while it is more or less plastic. It is, in the main, a medium-temperature coking process. The oven is horizontal, about 40 feet long, 27 inches high, and 17 inches wide. Its bottom, made of iron, consists of a reciprocating conveyor, to which are attached heavy cast iron fins acting as a ram to force a charge of coal at regular intervals into one end of the retort, compress it during coking, and discharge the coke at the other end. The temperatures may be graded from end to end of the oven. It is claimed that remarkably dense coke has been made thus from the Illinois type of coal, usually considered poorly coking. The oven has not been operated commercially.

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[19] Invented by L. L. Summers, 140 Nassau St., New York.

Chapter 10.

The Heating of By-Product Coke Ovens.

Amount of Heat Supplied.

Without exception, all types of by-product coke ovens are heated by the combustion of gas in the walls flanking the oven chamber on two sides. Usually a quantity of heat of 1,050 to 1,400 B.t.u. per pound of coal is supplied to the heating walls in the fuel gas. In cases of exceptional efficiency, and good utilization of the heat of the waste gas, somewhat less than the lower amount named may be used. Of this heat, from 22 to 28 per cent. is lost in the chimney gases and a further amount (not accurately known, but perhaps approximately 8 to 12 per cent.) by radiation, the remainder passing into the charge of coal to effect its carbonization. (See Fig. 109, page 245.)

As appears from considerations in Chapter 5, treating of the theory of carbonization (pp. 87-94), the heat imparted to the coal is devoted essentially to raising its temperature to a practically efficient carbonizing point, and to the heating of the gas and decomposition products. Although heat, at certain stages in carbonization, may be absorbed in decomposition and in chemical transformations in the coal substance, it is again liberated and the reactions in their resultant effect are, in a small degree, exothermic rather than endothermic. An appreciable part of the heat, however, becomes latent in steam and other vapors which pass out of the carbonizing mass to be later condensed. In this form, and in the sensible heat of the oven gas and discharged coke, practically all of the heat imparted to the coal is dissipated.

Distribution of the Heat Outlay.

(Not properly a "Heat Balance.")

The heat therefore that is put into the oven flues or heating walls is an outlay devoted, without attempt at recovery, to effecting the transformation of the coal into new fuel products. Quantitatively, it comprises (1) a major portion (700 to 900 B.t.u. per pound of coal), devoted to raising the temperature of the charge, this being practically irreducible for a given kind of coal, and (2) a minor portion (350 to 500 B.t.u. per pound), which is lost in the waste gases and by radiation, and which is variable according to the degree of efficiency in the oven heating.

Heat Used in Coking (in By-Product Ovens).

(See also Figure 109.)

Assuming an average coal mixture of 29-30 per cent. volatile matter, 3-4 per cent. moisture, regenerative ovens, and a total of 1,225 B.t.u. used per pound of coal, to effect the coking (this including both the heat of combustion of the fuel gas, and any heat of exothermic reactions in the coal).

	B.t.u.	Per Cent.
A.—Heat passing through wall into charge, or developed within charge appears in:		
(1) Sensible heat of *coke*	450	36.7
(2) Heat of *oven gases* and *vapors*		
(a) Sensible heat of gas	170	13.9
(b) Latent and sensible heat of water vapor and tars	155	12.7
(3) Radiation from oven interior, etc.	40	3.3
B.—Heat lost from flues:		
(1) Sensible heat of dry waste gases	150	12.2
Latent and sensible heat of water vapor, etc.	170	13.9
(2) Radiation from brickwork, etc., and miscellaneous losses	90	7.3
	1,225	100.0

The Heat Balance—Its Purpose and Manner of Derivation.[1]

A heat balance, in correct usage, is a calculation (based on actual measurement) of the input and outgo of heat energy in a unit of industrial operation, or other example of heat exchange, wherein, following upon the Law of Conservation of Energy, the amount of heat imparted to the process must be fully accounted for in the amount taken from it or stored therein as potential energy.

In the coking of coal the input of energy includes not only the heat of combustion of the fuel by which the oven is heated, but also, since the coal is to undergo decomposition and consequent transformation of its potential energy, the additional item of total energy of the raw coal represented by its heat of combustion.

In like manner the outgo of energy must be regarded as including not only the sensible heat, and heat of vaporization, of the materials produced (coke, gas and by-products), and that of the waste chimney gases, together with heat transferred to the surrounding air by "radiation," but in addition, the potential energy of the products represented by their aggregate heat of combustion. Exceedingly complex chemical reactions occur in coal carbonization involving interchange of stored energy, which enters into the heat balance.

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[1] Heat balances in coal carbonization have been discussed or offered by the following: J. K. Munster, *Blast Furnace and Steel Plant,* 1923, pp. 389-392; D. W. Wilson, Forrest and Herty, *Journal of Industrial and Engineering Chemistry,* 15, 251 (1923); E. G. Stewart, *Gas World* (London), Apr. 3, 1920, and a note referring to same, by H. Hollings in *Gas Journal* (London), Apr. 13, 1920.

This being true, it follows that a heat balance in coal carbonization requires first a *weight balance.*

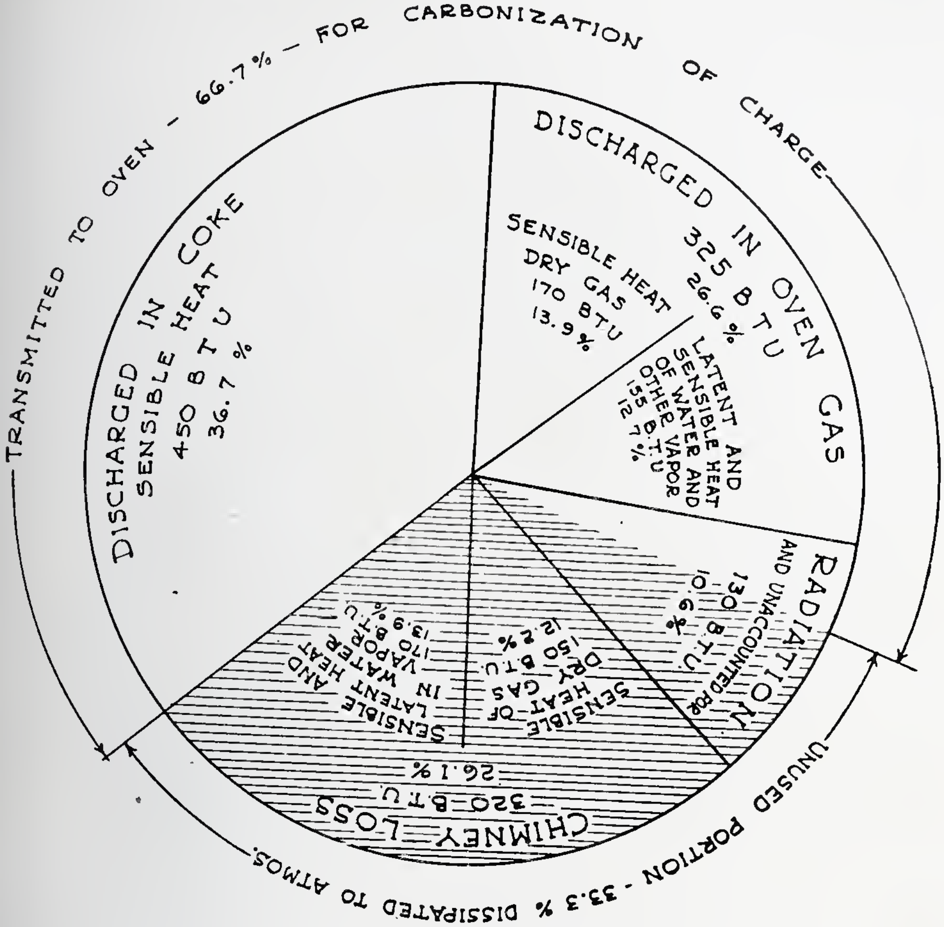

FIG. 109.—Approximate Average Distribution of the Heat Put into the Heating Flues of a By-Product Coke Oven (on the basis of 1225 B.t.u. total input per pound of coal carbonized).

Owing to the difficulty in commercial coking operations of collecting and measuring accurately all of the products, for example the deposited carbon and soot, the gas (without losses), the coke dust, and the water of decomposition, a measured weight balance, free from approximations and suitable for application in deriving a satisfactory heat balance, is industrially impracticable. Without assurance of the full recovery of combustible products for completion of the weight balance, a true heat balance is unattainable.

This has been lost sight of by many investigators who have attempted to balance the input and outgo of energy in by-product coke oven operation or other coal carbonization processes, by inserting an item for endo-thermic or exo-thermic effect of the chemical reactions of carbonization (shown by difference), neglecting at the same time to establish a complete weight balance and thus guard against unaccounted losses of material.

The uncertain item of heat losses by transfer to the air from oven interiors and brick work, the so-called "radiation losses," is a difficult one to measure or to estimate. This is an added reason why the attainment of a true heat balance in an industrial coking operation, is, in the present state of the art, extremely difficult if not impracticable.

If the balance be confined to the sensible heat recovered in the products as against the heat imparted in the fuel gases burning in the oven flues, and it be assumed that "radiation" loss can be measured with a fair degree of accuracy,[2] it is possible to derive thus, by difference, an item of "unaccounted-for" loss or gain. This probably does not, however, represent closely the reaction heat exchange of carbonization, since the weight balance showing the potential energy respectively in coal and its products, may, and probably does in the majority of cases, present also an "unaccounted-for" difference which may be of similar or opposite sign. The total heat input, including, for example, that accidentally incurred through leakage of air, is difficult of practical determination.

In the above-presented tabulation therefore of the distribution of heat outlay in by-product coking the intent is not to present a heat balance. An estimate of "radiation" losses is frankly not attempted, but this loss is set down for convenience, together with "unaccounted-for" losses, as making up the remaining balance of the heat input shown by difference. The "unaccounted-for" losses include any possible endo-thermic or exo-thermic reaction effect, which would be definitely shown only by the additional data of an accurate weight balance.

Based only on general averages of industrial practice, such derivation of reaction heat effect by difference would have little if any value. Based on actual measurements in a concrete instance it *may* lead to results of value, if radiation losses can be closely measured, heat input fully traced, and a complete and reliable weight balance secured.

The Heat Losses. For reducing heat losses chief attention has been paid to the waste gases and radiation, so that in present practice these losses have become the minor part, as above indicated. Under old conditions, when 1,800 B.t.u. or more were supplied per pound of coal coked, or as high as 60 per cent. of the gas from the ovens, there was much greater loss in the waste gases, and the portion of the heat utilized in the oven was frequently less than half of that put into the flues, instead of 65-70 per cent. as in modern practice.

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[2] H. J. Hodsman and J. W. Cobb, in a paper before The (British) Institution of Gas Engineers, 1920 (*Gas World*, June 5, 1920, 510), make estimates of probable heat losses by "radiation" in connection with a proposed industrially-scaled gas-producer using oxygen in the blast. Their estimates by several methods lead them to fix upon a figure of approximately 1.0 per cent. of the heat value of the coal treated as the probable "radiation" loss in this type of apparatus.

Coke oven carbonization, however, if it is to widen its field of usefulness and become an efficient means of fuel application, must go further in economizing the heat expenditure for producing modified fuels and by-products. Losses other than those in the waste gases are important. The sensible heat of the coke, at least one-third of all of the heat put into the oven walls, is by present methods a total loss; as is also the heat in the oven gas and vapors, nearly as large with some coals as that in the coke. These items, therefore, offer comparatively large opportunity for savings, if practicable means can be devised to apply the heat thus discharged from the oven. Attempts have been made to recover the heat of the coke by special (patented) inclosed quenchers, one of the latest proposals (reported as having been put in operation in Germany) being the Sulzer "dry quencher" (*Gas und Wasserfachmänner,* 64 (1921), 204-5) which holds the hot coke while a current of inert gas is blown through it by a fan and the heat thus carried to a waste-heat boiler.

As noted, the loss of heat through the waste stack gases has been reduced materially by improvement of heat recovery in regeneration. The improved utilization of this sensible heat in preheating the air for combustion by means of recuperators and regenerators, together with careful regulation of the amount of excess air, has greatly reduced these losses. In good practice now (see Figure 109) this item seldom exceeds ¼ of the total heat supplied to the flues.

Dissipation of heat into the atmosphere, often called "radiation," from the oven brickwork is an important source of loss. It can be minimized by attention to the problems of heat insulation in design of the battery, by the use of air flues in the insulating brickwork which return part of the heat by the preheated air to the combustion flues, and by care in restricting the time that oven doors remain off or the oven interiors are otherwise exposed.

The intermittent character of coke oven operation, the periodic emptying and filling of the highly heated brick chamber and the charging of the hot oven with cold wet coal, place not only upon the structure but upon the operating efficiency a severe strain. A large weight of heated brickwork in the battery, provided, in certain types by the heavy division walls, acts as a storage reservoir of heat which promotes the maintenance of an even temperature in the heating walls, reduces heat losses, and assists in bringing up the temperature rapidly after charging the oven.

Transmission of Heat to the Coal Charge.

The main problem in coke oven heating is to transmit the requisite amount of heat to all sections of the coal charge with a maximum of uniformity, a minimum of heat losses, and at a rate as high as may be consistent with safety of brickwork and a good quality of coke and other products. The rate of heat transmission (through oven wall and the partly coked charge) together with the width and other dimensions of oven and the nature of the coal, determines the coking time and the daily output per oven. Coking time is ordinarily controlled by change of temperature in the heating flues by variation of the rate of burning of gas, the temperature, other things being equal, fixing the rate of heat transmission to the coal.

Increase of daily output per oven means the lowering of capital and operating charges per ton of product per year, the essential factor in plant economy.

The rate of heat transmission through the brick of the oven wall is not concerned directly in the quality of coke which an oven may produce. In other words, one type of oven wall, as against another, so far as their heat-transmitting qualities are involved, does not produce better or poorer coke. The facility of heat transmission, however, does affect the degree of temperature required in the flues, in order to maintain the desired temperature on the interior of the oven wall. This wall temperature next to the coal determines the rate of driving the heat through the coking mass, which rate influences in a measure coke quality. But whatever may be the design of heating wall, be it flueless or flued, having upward or downward or horizontal flame passage, and whatever its qualities for heat transmission, these latter have no influence on quality of coke and output of coke, as long as the temperature of the wall *inside* of the oven is maintained at a desirable degree and uniform. One type of oven may secure this desirable temperature with less expenditure of heat than another, but this is a matter of heat economy and has nothing to do with the relative qualities of coke produced, provided the requisite optimum temperature is maintained. The contrary is frequently heard in the commercial claims for particular oven systems.

The transmission of heat from within the flue through the oven wall to the coal is strictly a matter of conduction. *The quantity of heat transmitted in unit time varies directly with the heat conductivity of the material, the temperature difference at the two surfaces and the area exposed to direct transmission, inversely with the distance between the two surfaces.* In bringing the heat *to* the coal, therefore, the relative conductivity and thickness of the brick in the wall are important factors. But in carrying it farther, that is, *into* the coal, another factor of greater importance enters, practically from the start of the coking period, namely, the slowly widening layer of coke between oven wall and raw coal, whose relative thickness, heat conductivity and absorptive power soon become of principal importance in the heat transfer.

Exact data of thermal conductivity of coke, or of partially coked coal, are not available, and would be of little value in this connection, if they were, since we deal here with heat capacity as a large element in conductivity (see below, page 250, "thermal diffusivity"). The temperature drop across the layer of coking coal is very large (1,500° F. or more) and a great proportion of the heat entering this layer is absorbed by the coke and other decomposition products as sensible heat, the minor portion passing through to the raw coal.

Thermal Conductivity of the Wall and of the Charge.

Heat must be imparted to the oven wall only at such a rate as it can be transmitted through it and *away from* it into the coking mass, otherwise the wall would continuously become hotter and finally melt, as has occurred not infrequently in practice. The limiting factor herein is not the conductivity of the wall, but the conductivity and heat capacity of the shell of coke and semi-coke surrounding the coking mass of coal. At the beginning of the coking period the relative conductivity of the wall material is an important factor, as long as the heat is rapidly taken away, but soon thereafter when conduction through the charge becomes slower, the high resistivity of the coke shell becomes the prime factor, overbalancing, within the limits of the materials commonly used, the relative conductivity of the wall.

As coke is a highly porous material, and in general the cell spaces in a mass are known to increase the resistance to heat transmission there can be no doubt that the coked and partly carbonized layers next the wall of an oven are relatively of a low order of thermal conductivity.

As is noted below in discussing transmission of heat from the burning gases to the wall, the resistance of the clinging film of gases on the wall surface is an exceedingly important factor in the rate of heat transmission. Inside of the oven, as well as in the flues, a film clings to the wall and exercises a large share of the total resistance to the passage of heat into the charge. G. A. Goodenough says (in L. S. Marks' *Mechanical Engineer's Handbook,* 1916, p. 302) in connection with the transmission of heat through boiler tubes, engine cylinders, etc., "At the surface of the plate there is a film of the hot fluid of indefinite thickness. This film offers a considerable resistance to the transmission. . . . The resistance of the fluid film depends upon the kind of fluid and the character of its motion. . . . The resistance of a film of hot gas is very high. It has been estimated that in certain cases 98 per cent. of the available temperature drop is required to force the heat through the gas film. . . . If the hot gas, as in a boiler tube, is given a high velocity, the resulting sweeping action partially destroys the film and decreases the resistance."

Further corroboration of this high-resistance film is given by W. H. McAdams and T. H. Frost, reporting on researches at the Massachusetts Institute of Technology, on "Heat Transfer."[3]

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[3] *Ind. and Eng. Chem.,* 14, 13 (1922).

"When a liquid or a gas is in contact with a solid there is strong evidence to show the presence of an adhering relatively stationary film of fluid on the surface of the solid, a film which becomes thinner as the velocity of the fluid parallel to the surface increases, but which breaks away from the solid only at very high velocities if at all. . . . Since most liquids and gases are exceedingly poor conductors of heat it is not surprising to find a large resistance to heat flow at the boundary surface . . . accompanied by a large drop in temperature at this point." (See also I. Langmuir, *Phys. Rev.*, 34, 421 (1912).)

The Heat-Transmitting Properties of Silica Brick.

Silica brick, now very largely used in America for coke oven wall construction, have at high temperatures, slightly higher thermal conductivity than fire-clay brick.[4]

The property of temperature "diffusivity," involving in addition to conductivity (k), the specific heat (c) and specific gravity (s) of the material in the relationship, k/cs, reveals a more marked difference between silica and fire-clay brick. Dougill, Hodsman and Cobb (*loc. cit.*) show for this property a value of .0098 for silica and .0079 for fire-clay, at 1,000° C. (1,832° F.). This means simply that in heating up the brick, during the stage preceding the attainment of constancy of temperature in the walls, the silica (being lower in gravity, approximately equal in specific heat, and slightly higher in conductivity), absorbs and transmits more rapidly than the clay-brick the heat applied

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[4] Dougil, Hodsman and Cobb (*Journal of the Society of Chemical Industry*, 34, 465-471 (1915)), have carefully determined the relative thermal conductivities of various refractory materials, presumably of English origin, at different temperatures. The following are their values for fire-clay and silica brick in the higher temperature range:

	Fire-Clay Brick (Hard-burned)	Silica Brick
Temperature range (from face to face)	510°–1,350°	440°–1,395° C.
Conductivity constant (K)	.0039	.0042
Chemical composition:		
SiO_2	66.0%	95.3%
Al_2O_3	31.0	2.0
Fe_2O_3	1.2	1.1
CaO	0.3	1.5
MgO	0.9	
Alkalies	1.0	

Note: The American silica brick of high grade—as used in the modern by-product coke oven—contain 97.0 per cent. or more of SiO_2 as compared to 95.3 per cent. in the English sample above cited, and are somewhat harder-burned (K. Seaver, "Manufacture and Tests of Silica Brick for By-Product Coke Ovens," *Trans. Amer. Inst. Min. Eng.*, 53, 125 (1915)). It is likely, therefore, that their thermal conductivity is somewhat greater than that of the English sample.

to it on the flue side of the oven wall. This is important at the beginning of the coking period when the wall has been chilled by a fresh charge of coal.

Silica brick, as compared to clay brick, are preferable for coke oven use, however, not primarily on account of their superior thermal conductivity or diffusivity, but especially by reason of their rigidity or low degree of distortion under load at high temperatures, together with the fact of their comparatively large expansion by heat up to 1,100° C. (2,000° F.) and small degree of expansion above that temperature, a combination of properties which if properly allowed for makes for tight walls. (See also pp. 164-5.)

American plants attain a much greater average coking rate and output per oven than English or other European plants, largely through this superiority of silica brick assuring tightness of the walls at the high temperature required. This advantage accrues only in relatively small measure from the slight difference in thermal conductivity or diffusivity of the wall material.

It has been established that the joints between brick in the oven wall exercise relatively a high resistance to heat transmission. Owing therefore to the predominating influences of the joints and of surface films on heat transfer through the oven wall, the question of relative thermal conductivities as between refractory materials commonly used in coke oven construction, becomes of lesser importance.

Transfer of Heat from Flames to Oven Wall.

For good results it is essential that the wall be heated uniformly. There must be no "hot spots," to cause more rapid coking in certain sections than in others. Such a condition produces coke of non-uniform quality and entails a risk of softening of the brickwork.

A high velocity of gas flow in the heating flues is held to be desirable for promoting uniformity of heating. Since the generation of heat occurs where the union of fuel with oxygen takes place, and an important part of this is near the points where gas is admitted, the heat there generated must be carried along and distributed by the rapid flow of gases.

Convection and conduction play the main rôle here, in transferring the heat from the flame to the oven walls. Radiation takes a part, and it is an important one when the flames are luminous, but in prevailing practice in America there is, at most points in the flue, a low degree of luminosity. This question has been vigorously discussed by W. H. Blauvelt, F. W. C. Schniewind and others in connection with a paper by the former, delivered to the American Institute of Mining Engineers, in 1912, on the new regenerative system of heating Semet-Solvay coke ovens.[5]

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[5] *Transactions Amer. Inst. Mining Engineers,* 44, 186, 187 and 196 (1912); also Bull. A. I. M. E. 1912, p. 1309 ff.

Heat passes from the hot moving gases to the wall chiefly by actual contact and conduction, the heat in the gases being carried along, however, from one part of the flue to another by convection. It is essential that there be such convection and distribution of heat by a rapid flow of gases, since otherwise the far reaches of the gas passages would be insufficiently and unevenly heated. W. H. Blauvelt says:[6] "Whether the heat is transferred by radiation or convection the uniform flow of the gases in this new system carries along and distributes the combustion so that no matter what temperature may be developed by the burning gases, the heat is carried away from the danger points—and there is in practice no tendency to hot spots or other irregularities."

An exceedingly important factor in the heat transfer is the stagnant or slow-moving layer of gases which clings to the flue walls, acting to retard conduction. (See page 249.) High velocity tends to lessen the effect of this film or stagnant layer.

Gas Velocities in the Heating Flues.

Comparison of the Vertical and Horizontal-flued Systems. In the two main types of flued oven wall, viz., the horizontal- and the vertical-flued, the conditions in respect to relative velocities of the burning gases and time of contact thereof with the surface to be heated differ so widely as to be worthy of special study. The principle involved is of such importance, that the relation of gas velocities to heat transfer proves to be a factor of large importance in the development of coke oven heating methods.

The Koppers oven flue (in the "Regular Type" Oven), by calculation of dimensions and of gas volumes passing[7] would appear to carry the hot gases of combustion at a velocity, roughly, one-twelfth of that in the Semet-Solvay flue, although the influences of draft and buoyancy of vertical columns of hot gases may affect the comparison considerably. The single Koppers flue, although at the same temperature, carries much less heat in a given time than the Semet-Solvay, but through the lower gas velocity presents also less surface to be heated per unit of time. The heat of the Koppers flue serves two oven walls instead of one, but it traverses only about 2.2 linear feet per second, as against 25-28 feet in the Semet-Solvay.

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[6] *Loc. cit.*, p. 196.

[7] In the Semet-Solvay modern regenerative oven approximately 1,700 cubic feet of fuel gas (coke oven gas) are admitted to each heating wall per hour, this being the total of the fractional amounts burned at five successive burners. The full amount of air (5 to 6 times the volume of gas), is introduced at one place, so that at 2,500° F. there passes through each progression of flues, practically 50,000 to 55,000 cubic feet of gases per hour, at all points therein, roughly 800-900 cubic feet per minute. This corresponds to a velocity of 25-28 feet per second; a unit of gas volume passes through the 6 flues (in contact with the entire wall of one oven) in 8-10 seconds.

In the Koppers oven (old type, coking 20 tons per 24 hours), 14 vertical flues (on coke side, or 16 on pusher side) in each heating wall burn 3,500 cubic feet of oven gas per hour, or 220-250 per hour per flue. At 2,500° F. approximately 6,800-7,800 cubic feet of hot gases per hour pass through each vertical flue, or 112-130 cubic feet per minute (1,820 cubic feet or more, per minute traversing the horizontal flue at its center). There is an average gas velocity in the vertical flues of approximately 2.1-2.3 feet per second, and a unit volume of hot gases requires an average period of 9 to 11 seconds to pass through the heating wall. The velocity in the horizontal flue near its center is about 23-24 feet per second.

There is to be noted particularly the important distinction between the two systems arising from the fact that the Semet-Solvay introduces the full quota of preheated air for each heating wall *at one point,* viz., at the beginning of the succession of narrow flues; while the Koppers admits the air, in the same quantity, in 14-16 parallel flues of a combined sectional area 27 times that of the Solvay flue. The distribution of the heat of the air is therefore in the Koppers system over a comparatively large area and it travels, as has been said, at much lower velocity. The flow of gas in the Semet-Solvay wall may be characterized as "in series" through a succession of 6 long adjacent horizontal flues, whilst that in the Koppers wall is "in parallel," upward through 16 short flues (or 14) in one-half, and downward through 14 (or 16) in the other half. The total flow of heat within the wall may be said to be, in the former, through a long narrow channel at high velocity, and in the latter through a wider and shorter channel (the combined width of the several flues in parallel) at much lower velocity.

The transfer of heat quantitatively is essentially the same in the two cases. Whether its distribution is more even throughout the area of the wall in the case of high velocity of gas flow does not appear definitely proven by the results of experience with the two types of oven. It may readily be seen, however, that the Semet-Solvay system, with its long horizontal flues and comparatively small number of gas burning inlets, is especially in a position requiring the aid of such expedients to promote uniform distribution of heat.

Notwithstanding structural limitations with regard to heating, the modern Semet-Solvay regenerative oven has attained an excellent record of performance as to coking rate (1.10-1.25 inches of oven width per hour) on comparatively large sized ovens (18½ to 21 inches in average width), without sacrificing heat uniformity or over-heating of the oven tops. Owing partly to the high gas velocity in the flues and partly to the heat storage factor afforded by the heavy division walls, their heating efficiency also has been high. In spite of high flue temperature (2,500°-2,550° F. in some instances), employed to attain the coking rates mentioned, the average consumption of fuel gas per ton of coal in modern Semet-Solvay practice compares favorably with the heat results in other ovens.

Control of Oven Heats.

The various points of heat regulation in the different oven systems are pointed out in connection with the description of these systems

(Chapter 9). Certain common features of the control exercised through manipulation of these points may be taken up here.

The regulation of oven heats constitutes probably the most important element in successful operation of by-product coke plants. This part of the operation, in the interest of good returns from the plant as a whole, requires superintendence and labor of a high order, trained in the principles and practice of combustion and fuel economy.

The gas pressure is regulated on each side of the battery to suit the requirements as to coking rate, and there are provided control cocks for each oven as a whole. Individual nozzles or burner valves or cocks regulating the fuel supply to each flue are also provided.

Draft on the entire battery is subject to regulation by a damper, and this is in some plants automatic. At each oven, also, where the regenerator or recuperator opens into the waste-gas flue, a damper always is provided to control the chimney pull on the heating flues for that one oven. In some of the vertical-flued ovens, each flue has individual draft control by a slide-brick at its top.

The quantity of air, furthermore, can, in most of the oven systems, be controlled at the inlet to regenerators and generally individually for each oven, by the use of so-called "finger-bars" across the opening.

It is essential to coördinate these three controls—gas pressure, draft, and air—in such manner as to produce uniformity and regularity of heating at the temperature desired.

Large pressure drop in the course of travel of the burning gases in the flues is to be avoided. It is likely to induce leakage in the wall. Such design of heating flues (in size and arrangement), of inlets and outlets, regenerator filling, etc., as will permit the requisite flow of hot gases (commensurate with the large oven charges of modern practice, and the use of the thinner fuel gases with high content of inerts) is essential to maintenance of a reasonably low pressure drop. It can be aided also by coördinated control of draft and air supply. Accentuation of the troubles arising from leakage in flue walls will thus be avoided.

Uniformity of heat throughout each oven is to be aimed at by careful inspection of conditions in individual flues and prompt attention to the remedying of defects, such as carboning, leakage, or improper regulation.

Performance in Oven Heating, by Various Plants.

The following records of oven performances, reported to the author by the plants concerned, must be discounted by allowance for the probability of variant conditions at the different plants, and for the possibility of such records being transient rather than normal for continuous operation. The nature and fineness of the coal, and its moisture content, the duration of the test run, the conditions pertaining before and after, and especially the degree of coking attained in the run, are factors not generally reported but having large influence on the heating results.

On Semet-Solvay regenerative ovens of the Lackawanna Steel Co., Lackawanna, N. Y. (19½ inches average width, 16 tons capacity), in 1921, during a special test period, under ideal conditions and most careful regulation, results are reported showing fuel gas consumption of 1,000 B.t.u. or less per pound of coal, with 18-hour coking time, and an average waste gas temperature of 640° F.

The carbonizing rate per oven thus in this performance was 21.3 tons of coal per 24 hours.

Becker's type of Koppers oven, at Chicago, Ill., 37½ feet long (between doors), 13¾ inches average width, with a coal charge of 11.7 tons, showed in 10 months' continuous running, in 1922 (according to information furnished by The Koppers Co.) an average capacity of 25.3 tons coal per 24-hour day, with average coking time of 11 hours; and with fuel gas consumption of 1,095 B.t.u. per pound of coal carbonized, flue temperature of 2,500° F., and waste gas temperature of 550° F.

Roberts ovens at Granite City, Ill., are reported to have carbonized regularly a 15-ton charge of Illinois-Indiana coal mixture in 15 hours, or 24 tons per 24-hour day, using fuel gas amounting approximately to 1,300-1,400 B.t.u. per pound coal carbonized (with recuperative heating).

Wilputte ovens, at South Chicago, Ill., new in 1919-20, 15 inches in average width and with coking time normally averaging 18 hours, are reported to have run in the year 1920 on an average fuel gas consumption of 35 per cent. of the total gas made. Benham (Kentucky) coal was used (90 per cent.), an excellent gas making coal, and blast-furnace coke was made.

It may be noted that the more recent oven installations, particularly of the Koppers type, are comparatively narrow (and in some cases higher and longer than those of prior date). (See also Table 61, Appendix.) With ovens of such dimensions, a greater carbonizing rate appears to be possible than with wider ovens.

Waste Gas Return to the Oven Flues, in the Koppers System.

There is being advocated in most recent Koppers oven practice, either producer gas heating, which results in relatively large volumes of combustion gases and therefore relatively high velocity, or, with coke-oven-gas heating, the return to the flues with the fuel gas and air of *waste gas* from the chimney. This practice has the effect of retarding combustion and distending the flames, by the dampening effect of the inert gases, nitrogen, CO_2 and water vapor, the two latter being of relatively high specific heat. It practically doubles also the volume of the gases and hence their velocity. The waste gas is introduced into the air regenerator, with the air, in such proportion as to reduce the oxygen content of the mixture from 20.9 per cent. to 10-12 per cent.

In those oven-heating systems (e.g. the Semet-Solvay, the Roberts, and a late type of the Piette) which make use of serial introduction of the fuel gas, there is attained at the secondary (and other following) burners, this same favorable condition of "dampened" combustion in an atmosphere containing inert gases. The gaseous products from combustion at the primary burners pass along with the air to the secondary burners, and exert the desirable retarding effect above mentioned. The high velocity in the Solvay flues increases this effect.

Regeneration and Recuperation of Waste Heat.

Classified in respect to methods of recovery of heat from the waste gases, there are three types of heating systems for by-product coke ovens: (1) Waste-heat, or cold-air ovens; (2) Recuperative ovens, and (3) Regenerative ovens.

The Waste-Heat, or Cold-Air Oven uses air either cold or slightly pre-heated by passage through "cooling ducts" in the sub-structure of the battery, or through a sole flue directly under the oven. The hot waste-gases are not utilized for preheating air, but are generally passed through boilers, or economizers, wherein their sensible heat serves to produce steam. It is found in Semet-Solvay practice (in which field chiefly has the waste heat type been used in America) that nearly twice as much fuel gas per ton of coal must be burned in the waste heat oven as in the regenerative oven. The average surplus gas, is, in the one, 30 per cent. of the total gas produced as against nearly 65 per cent. in the other. The heat of the waste gases from the oven flues is probably three times as much in the former as it is in the regenerative system, a large part of this excess being ordinarily recovered, however, in boilers.

The waste heat oven has its field of usefulness, and is economical under circumstances not presenting an outlet for surplus oven-gas sufficient to justify the additional cost of regenerative ovens.

The Recuperative Oven. As applied to waste heat recovery in coke oven practice, the term "recuperative" designates that process of preheating the air for combustion, wherein the hot waste gases, after leaving the oven heating flues, flow *continuously* through a set of narrow passages, surrounding or adjoining other passages for the air to be heated. In order that the air may be heated to the highest possible temperature the two currents are in counter direction, so that the incoming cool air first meets the waste gas near its exit, and abstracts from it as much as possible of its remaining heat, then passes on toward the point of entrance of waste gas, approaching constantly nearer the temperature of the entering waste gas. The respective quantities and heat capacities of the waste gases and required air are carefully considered in connection with the designing of a recuperator in order that the gas velocities and relative dimensions of the passages may be suitably adjusted.

The Semet-Solvay has been the principal coke oven system to use the recuperative plan in America, although the Roberts and the Piron also make use of it. The former (Semet-Solvay) has not ordinarily attempted maximum recuperation of the waste gas heat but has applied a portion thereof to boilers or feed-water heaters. Among the plants of this type in this country (perhaps eight or ten in number) the recovery of surplus gas generally averages 40 per cent. In the Roberts plant at Granite City, Ill., using Illinois coal, it is claimed that 50 per cent. surplus gas has been regularly obtained (with no recovery in the form of steam).

Heat economy, however, is, in general, not found as great with the recuperative as with the regenerative system—the latter giving higher temperatures and faster coking rates. In the cycle of heat transfer from hot gases to refractory material, to incoming air, the regenerative system has an advantage over the recuperative, in that it presents a greater weight and greater surface of solid material in relation to the gases passing, to act as a medium in the transfer of heat from waste gas to air. With the high temperatures commonly attained in coke oven operation, it is ordinarily not practical with recuperation to bring the temperature of the air as close to that of the waste gases as is attained with regeneration.

Recuperators present also the problem of maintaining gas-tight partition walls between hot gas and air flues, these walls being thin, unequally heated in different parts, and exposed to unequal gas pressures on the two sides.

A great advantage in recuperation, however, lies in the continuous character of its operation, and as compared to regeneration the nearer approach to constancy of pre-heat in the air (other things being equal), and of off-heat to the chimney.[8]

The Regenerative Oven. The Siemens principle of "regeneration" of waste heat was adapted first successfully to by-product coke oven heating by Hoffman, in Germany, in 1881.[9] The first application in America was in the Otto-Hoffman ovens.

By the regenerative system, the heat of the waste gas is stored by passing the gas, for a period, through one of two checquer brick chambers, after which period, and at regular intervals, the flow of gases is shifted to the other chamber, and air to be preheated is admitted through the first. During the alternate periods, when hot gases are not flowing, air passes through the hot checquers on its way to the combustion flues, and takes up the heat therein stored. The air flow to the regenerator chambers must be shifted from one to the other at the same time as the waste gas is shifted from the alternate chambers.

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[8] An exposition of the general principles of recuperation and regeneration, and of the design of recuperators is given by Henry O. Loebell, in the *American Gas Association Monthly*, 2 (1920), pp. 499 and 565.

[9] According to Dr. Ernst F. Dürce, "Die Neueren Koksofen," Leipzig, 1892, p. 60.

It is evident that in this system a certain amount of fluctuation must occur in the degree of preheat imparted to the air, since from beginning to end of the reversing period the available heat in the checquer brick continually diminishes, and the amount of air passing per unit of time remains the same. (See Figure 74.) The temperature in the combustion flues of the oven must accordingly diminish gradually during each period (usually one-half hour) and rise again rapidly just after reversal. This fluctuation is generally, however, not through a wide range. Actual measurements at 1-minute intervals in the flues of Koppers ovens[10] during a period of several hours have shown a mean variation of 75° C. (135° F.) from low to high point in the reversal period (Figure 36).

In the design of regenerators careful consideration is necessarily given to the heat capacity and rate of heat absorption by the checquer brick (usually of silica), their manner of placement in the chamber whether for baffling of the gas currents or for permitting of free passage in accordance with the calculated suitable velocity, the varied spacing of the checquers for securing uniform flow of air to the combustion flues, the relative volumes, heat capacities and velocities of the waste gas and air, and the question of pressure drop in the regenerator, as requiring certain chimney draft. The prime object in the regenerator of a by-product coke oven is to abstract as much heat as possible from the waste gases without encumbering too greatly the structure, or impeding too much the flow to the stack. An important element in its duty is to permit a uniform flow of air and uniform degree of preheat in the air flowing to the various combustion flues of the oven.

Temperatures lower by 600°-700° F. or 330°-390° C. than that of the combustion flues are in good practice obtained in the preheated air through regeneration.

There are various factors entering into this relationship, to affect the balance between heat abstracted from waste gas and heat taken up by the air. From Tables 26 to 32, pages 260-6, it may be seen that the volume of air used is less than that of the waste gases produced, and its equivalent heat capacity (weight times mean specific heat) is also less than that of the waste gases. In case of coke oven gas (with 10 per cent. excess air) the ratio of the heat capacity of the air to that of the waste gases, over a similar temperature range, is as 10 to 12½. Since, however, some of the heat of the waste gases is lost by radiation and the air temperature ordinarily is raised through a somewhat greater range than that through which the waste gases fall, there is approximately a balance.

In case of producer gas (see Table 30), there is again approximately a balance when gas and air are both pre-heated by the "off heat" of the waste gases, but if only the air is pre-heated the balance is disturbed, since its heat capacity is very much less than that of the waste gases. A large amount of heat, therefore, is lost in the waste gases to the stack, and the temperature in the combustion flues is lower than would otherwise be the case. Through the high degree of preheat in the air which regeneration makes possible, ovens may be operated more efficiently and more rapidly than when cooler air is used.

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[10] Tests by Bureau of Standards and Bureau of Mines, at St. Paul, Minn., 1918; Technol. Paper No. 137, Bureau of Standards (1919), p. 19.

The rate of coking, and therefore daily output, is accordingly greater with the regenerative type, its consumption of fuel gas is less, and it offers no serious difficulties in securing uniformity of heating. These advantages have given it the preference in America. Nearly 90 per cent. of all by-product coke in this country is made in regenerative ovens.

The Use of Externally Produced Gases (Producer Gas, Blast Furnace Gas, etc.) in Coke Oven Heating.

It is frequently advantageous from an economic standpoint to preserve the whole of the coal gas resulting from carbonization for distribution outside of the plant. In such case, a leaner gas and one which under the circumstances is cheaper per unit of B.t.u.'s, such as producer gas, blast furnace gas, or blue water gas, is burned in the heating flues, and under proper conditions any of these proves satisfactory for the purpose.

Producer gas and blast-furnace gas, on account of their large content of inert gases and their low heating value per cubic foot, need to be burned at higher rates than coke oven gas, and must be preheated in order to give practically the requisite temperatures. Blue water gas can be used satisfactorily without preheating.

Combustion Data.

In Table 26 are given typical percentage compositions of the various fuel gases compared to that of coke oven gas, also their calculated theoretical flame temperatures, and relative volumes of required air and of the products of combustion.

Calculation of Flame Temperatures, and Comparison of Gas Volumes, Heat Capacities, etc. The following method of calculation has been used to deduce the "ideal" flame temperatures given in the following table:

There is assumed a certain excess of air over the theoretical, say 10 per cent., or 25 per cent., and a certain degree of preheat, say 1,700° F., 100 cubic feet (in case of coke oven gas), burned with 540.2 cubic feet of air; also there is the assumption that no loss of heat occurs

TABLE 26.

Composition and Flame Temperatures of Various Fuel Gases, Used in Heating By-Product Coke Ovens.

Percentage Composition:	Coke Oven Gas *	Producer Gas †	Blast Furnace Gas	Blue Water Gas
CO_2	2.0	6.8	11.5	4.5
C_2H_4, etc.	3.0	.0	.0	.0
O_2	.3	.0	.0	.4
CO	6.0	23.5	27.5	39.5
CH_4	32.0	.4	.0	2.0
H_2	51.5	14.0	1.0	50.0
N_2	5.2	55.3	60.0	3.6
B.t.u. per cubic foot (gross)	564.3	125.7	92.2	311.1
“ “ “ “ (net)	507.3	118.6	91.7	285.2
Air required for combustion (relative volume)	4.911	0.936	0.682	2.333
Volume of products of combustion (including water vapor)	5.630	1.747	1.539	2.880
Calculated flame temperature (using cold air, 10 per cent. excess)	3,310° F.	.....	.....	.....
Calculated flame temperature (using air at 1,700° F., 10 per cent. excess)	4,145° F.	3,305° F.	.....	4,200° F.
Calculated flame temperature (using air at 1,700° F., 25 per cent. excess)	3,960° F.	.....	.....	.....
Calculated flame temperature (gas and air both preheated)	.....	3,840° F.‡	3,500° F.§	.....

* “Straight run of oven” gas, debenzolized, from average Eastern coal mixture—85:15 (high volatile: low volatile).

† From small coke and breeze, in pressure producer, with medium quantity of steam.

‡ 10 per cent. excess air, both gas and air assumed at 1,700° F.

§ 25 per cent. excess air, both gas and air at 1,700° F.

Note: These flame temperatures have been calculated without taking into account the partial dissociation of CO_2 and steam which at these temperatures may result from the reversibility of the gas reactions.

to the surroundings, and that combustion is complete. The temperature of combustion (in excess of 64° F., on which base point the heating values of the fuel gas are fixed) is, then, the quotient obtained by dividing the total heat of the fuel mixture (sensible heat of the air plus heat of combustion) by the heat-capacity value (weight times mean specific heat) of the gaseous products and water vapor.

Since the specific heats of gases, and particularly of CO_2 and water vapor, change materially with rise of temperature, it is necessary to use the mean specific heat, computed for the temperature range through which the products of combustion pass (setting the maximum approximately by trial values). The data of Le Chatelier for mean specific heats as used by F. C. Binnall in American Fuels, Bacon and Hamor, Chapter 18, volume II, p. 1051, “The Relative Values of Gaseous Fuels,” have served for these calculations.

Tables 27-32 show the calculations of various combustion mixtures and their temperatures of reaction.

TABLE 27.

Combustion of Coke Oven Gas with Preheated Air, at 1,700° F. (100 Cubic Feet Gas with 10 Per Cent. Excess Air).

Air: 540.21 cubic feet dry (110 × 4.911) plus 7.49 cubic feet water vapor, (70 per cent. saturation at 64° F.).

Constituent	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-1,700° F.	Equivalent Heat Capacity	Sensible Heat of Air (B.t.u.)
Oxygen	112.90	9.5551	.2288	2.187	
Nitrogen	427.31	31.7495	.2614	8.301	
Water vapor	7.49	.3565	.586	.209	
	547.70	41.6611		10.697	17,500

Fuel Gas: 100 cubic feet (assumed at 64° F.). (Carrying .066 pound water vapor, at 70 per cent. saturation.)

	Cubic Feet	Weight (Pounds)	Net Heat of Combustion (Per Cubic Foot)	Total Heat of Combustion
CO_2	2.0	.2327		
C_2H_4, etc.	3.0	.231		
O_2	.3	.0254		
CO	6.0	.4444		
CH_4	32.0	1.3549		
H_2	51.5	.2730		
N_2	5.2	.3863		
	100.0	2.9477	507.3	50,730

Products of Combustion:

	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0°–4140°	Equivalent Heat Capacity	Total B.t.u. (above 64° F.)
CO_2	47.5	5.560	.382	2.120	
Water	130.8	6.228	.812	5.064	
Oxygen	10.5	.889	.254	.226	
Nitrogen	432.5	32.136	.290	9.300	
	621.3	44.813		16.710	68,230

Temperature of Combustion: $\frac{68{,}230}{16.710} + 64 = 4{,}145°$ F.

TABLE 28.

Combustion of 100 Cubic Feet Coke Oven Gas with 25 Per Cent. Excess Air (Preheated to 1,700° F.).

Air: 613.88 cubic feet (125 × 4.911) (dry) + 8.51 cubic feet water vapor (70 per cent. saturation at 64° F.).

Constituent	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-1,700° F.	Equivalent Heat Capacity	Sensible Heat of Air B.t.u.
Oxygen	128.30	10.858	.2288	2.4853	
Nitrogen	485.58	36.079	.2614	9.4332	
Water vapor	8.51	.405	.586	.224	
	622.39	47.342		12.1425	19,863

Fuel Gas: 100 cubic feet (at 64° F.) (Carrying .066 pound water vapor, at 70 per cent. saturation.)

	Cubic Feet	(Pounds)	Total Heat of Combustion
CO_2	2.0	.2327	
C_2H_4, etc.	3.0	.2310	
O_2	.3	.0254	
CO	6.0	.4444	(at 507.3 B.t.u. net per cubic foot)
CH_4	32.0	1.3549	
H_2	51.5	.2730	
N_2	5.2	.3863	
	100.0	2.9477	50,730

Products of Combustion:	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-3,950° F.	Equivalent Heat Capacity	Total B.t.u. (above 64° F.)
CO_2	47.5	5.560	.372	2.068	
Water	131.8	6.275	.792	4.970	
Oxygen	25.9	2.192	.252	.551	
Nitrogen	490.8	36.461	.288	10.518	
	696.0	50.488		18.107	70,593

Temperature of Combustion:

$$\frac{70{,}593}{18.107} + 64 = 3{,}960° \text{ F.}$$

TABLE 29.

Combustion of Producer Gas, Cold, with Preheated Air (at 1,700° F.).

Air (10 per cent. excess): 102.96 cubic feet (110 × .936) (dry) + 1.45 cubic feet water vapor (70 per cent. saturation at 64° F.).

Constituent	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-1,700° F.	Equivalent Heat Capacity	Sensible Heat of Air B.t.u.
Oxygen	21.519	1.8212	.2290	.4167	
Nitrogen	81.441	6.0503	.261	1.5815	
Water vapor	1.45	.0680	.586	.0400	
	104.410	7.9395		2.0382	3,334

Fuel Gas: 100.0 cubic feet (assumed at 64° F.) (dry) + 1.40 cubic feet water vapor (70 per cent. saturation at 64° F.).

	Cubic Feet	Weight (Pounds)	Net Heat of Combustion (Per Cubic Foot)	Total Heat of Combustion
CO_2	6.8	.7913		
CO	23.5	1.7406		
CH_4	.4	.0169		
Hydrogen	14.0	.0742		
Nitrogen	55.3	4.1082		
Water vapor	1.40	.066		
	101.40	6.7972	118.6	11,860

Products of Combustion:

	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-3,300° F.	Equivalent Heat Capacity	Total B.t.u. (above 64° F.)
CO_2	30.7	3.573	.342	1.222	
Water vapor	17.7	.840	.734	.616	
Oxygen	2.05	.174	.245	.042	
Nitrogen	136.74	10.158	.275	2.801	
	187.19	14.745		4.681	15,194

Temperature of Combustion: $\frac{15,194}{4.681} + 64 = 3,305°$ F.

TABLE 30.

Combustion of Producer Gas Preheated to 1,700° F., with Air (10 Per Cent. Excess) at 1,700° F.

Air (10 per cent. excess): 102.96 cubic feet (110 × .936) + 1.45 cubic feet water vapor (70 per cent. saturation).

Constituent	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-1,700° F.	Equivalent Heat Capacity	Sensible Heat of Air B.t.u.
Oxygen	21.519	1.8212	.229	.4167	
Nitrogen	81.441	6.0503	.261	1.5815	
Water vapor	1.45	.0680	.586	.0400	
	104.410	7.9395		2.0382	3,330

Fuel Gas: 100 cubic feet + 1.40 cubic feet water vapor (70 per cent. saturation).

Constituent	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-1,700° F.	Equivalent Heat Capacity	Sensible Heat of Gas B.t.u.
CO_2	6.8	.7913	.267	.2113	
CO	23.5	1.7406	.260	.4526	
CH_4	.4	.0169	.937	.0159	
Hydrogen	14.0	.0742	3.617	.2684	
Nitrogen	55.3	4.1082	.260	1.0681	
Water vapor	1.4	.066	.586	.0387	
	101.4	6.7972		2.0550	3,362

Products of Combustion:

	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-3,850° F.	Equivalent Heat Capacity	Total B.t.u. (above 64° F.)
CO_2	30.7	3.573	.369	1.320	(Adding the net heat of combustion of 100 cubic feet fuel gas, viz., 11,860 B.t.u.)
Water vapor	17.7	.840	.784	.658	
Oxygen	2.05	.174	.250	.043	
Nitrogen	136.74	10.158	.285	2.895	
	187.19	14.745		4.916	18,552

Temperature of Combustion: $\frac{18,552}{4.916} + 64 = 3,840°$ F.

TABLE 31.

COMBUSTION OF BLAST FURNACE GAS, PREHEATED TO 1,700° F., WITH AIR AT 1,700° F. (25 PER CENT. EXCESS).

Air: 85.25 cubic feet (1.25 × 68.2) + 1.20 cubic feet water vapor (70 per cent. saturation).

Constituent	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-1,700° F.	Equivalent Heat Capacity	Sensible Heat of Air B.t.u.
Oxygen	17.82	1.5081	.229	.3451	
Nitrogen	67.43	5.0094	.261	1.3095	
Water vapor	1.20	.0565	.586	.0333	
	86.45	6.5740		1.6879	2,762

Fuel Gas: 100 cubic feet (dry) + 1.40 cubic feet water vapor (70 per cent. saturation).

Constituent	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-1,700° F.	Equivalent Heat Capacity	Sensible Heat of Air B.t.u.
CO_2	11.5	1.3383	.267	.3573	
CO	27.5	2.0369	.260	.5296	
Hydrogen	1.0	.0053	3.617	.0192	
Nitrogen	60.0	4.4574	.260	1.1589	
Water vapor	1.4	.0660	.586	.0387	
	101.4	7.9039		2.1037	3,442

Products of Combustion:

	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-3,500° F.	Equivalent Heat Capacity	Total B.t.u. (above 64° F.)
CO_2	39.00	4.5384	.3515	1.5952	(Including net heat of combustion 100 cubic feet fuel gas, viz., 9,170 B.t.u.)
Water vapor	3.60	.1702	.7500	.1273	
Oxygen	4.46	.3774	.2475	.0932	
Nitrogen	127.43	9.4668	.2812	2.6622	
	174.49	14.5528		4.4779	15,380

Temperature of Combustion: $\frac{15{,}380}{4.478} + 64 = 3{,}500°$ F.

TABLE 32.

Combustion of Blue Water Gas with Air at 1,700° F. (10 Per Cent. Excess).

Air: 256.63 cubic feet (233.3 × 1.10) + 3.60 cubic feet water vapor (70 per cent. saturation at 64° F.).

Constituent	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-1,700° F.	Equivalent Heat Capacity	Sensible Heat of Air B.t.u.
Oxygen	53.63	4.5387	.229	1.0384	
Nitrogen	203.00	15.0812	.261	3.9422	
Water vapor	3.60	.1695	.586	.0992	
	260.23	19.7894		5.0797	8,308

Fuel Gas: 100 cubic feet (dry) + 1.40 cubic feet water vapor (70 per cent. saturation).

	Cubic Feet	Heat of Combustion
CO_2	4.5	(At a net value per cubic foot of 285.2 B.t.u.)
Oxygen	.4	
CO	39.5	
Methane	2.0	
Hydrogen	50.0	
Nitrogen	3.6	
Water vapor	1.4	
	101.4	28,520

Products of Combustion:

	Cubic Feet	Weight (Pounds)	Mean Specific Heat 0-4,200° F.	Equivalent Heat Capacity	Total B.t.u. (above 64° F.)
CO_2	46.0	5.3530	.385	2.0609	
Water vapor	59.0	2.8090	.816	2.2921	
Oxygen	5.28	.4468	.254	.1135	
Nitrogen	206.6	15.3477	.289	4.4355	
	316.88	23.9565		8.9020	36,828

Temperature of Combustion: $\frac{36,828}{8.9020} = 4,136 + 64 = 4,200°$ F.

The Effect of Increasing Excess Air in the Heating Flues.

Improper control of gas and air mixture and the introduction of an undue excess of air into the combustion flues affects seriously the heat economy. Not only does more heat escape through the stack in the added volume of hot waste gases, but temperatures are lowered in the flues and thus a higher rate of burning is required if they are to be maintained. From the data of Tables 27-8 comparison may be made of the relative heat capacities of air and waste gases, the latter being enough greater in correct practice to give the practical maximum of preheat in the air during regeneration. An excess of air over the proper ratio, say for example 10 per cent., may theoretically cause a loss of 5 to 10 per cent. heat, on the basis of total fuel gas used (varying according to the kind of fuel and other conditions). Owing to the somewhat smaller range of temperature ordinarily in the drop of the waste gases during regeneration, than in the heating of the cold air, and also to a certain amount of radiation loss, the total heat of the waste gas should be greater than that of the air, or of air plus fuel in case the latter is preheated also.

Producer Gas Heating.

It is to be noted that with producer gas firing (gas and air both being preheated to 1,700° F.) (Table 30), the theoretical flame temperature is lower by about 300° F. than with coke oven gas (with preheated air alone) (Table 27). Actual flue temperatures, however, as between the two kinds of fuel, may not differ as much as this, or at all, since an excess of temperature is in either case available by using a rate of burning sufficiently high. On the other hand, producer gas, unheated, with heated air, although its theoretical flame temperature (3,300° F.) is as high as that of a coke-oven-gas-cold-air flame which has served well in oven heating, does not in practice give a high enough temperature for successful coking operation; it requires, when cold, so high a rate of burning and thus the formation of so large a volume of combustion gases, that excessive gas velocities result, unsuited, in vertical-flued ovens, to the successful transfer of heat. The burning of cold producer gas entails great waste of heat also through the fact that the air alone has insufficient capacity to regenerate the waste-gas heat, and unless boilers or economizers are used, much of the latter escapes through the stack. (See Table 29.)

There are technical, as well as economic, advantages in the use of producer gas, compared to that of oven gas. Irregularities in flow and accidental variation in adjustments have, with this gas, less influence on flue temperatures, owing to its lean character; the absence of hydrocarbons in the gas removes the nuisance of carbon deposits at gas inlets; it is possible to operate with closer approximation to theoretically correct air-gas mixture.

The temperature also of waste gas is ordinarily lower, but this gain is in a measure off-set by a loss due to the greater volume and heat capacity of the waste gases, compared to those from oven-gas firing. This additional loss through the waste gases is aggravated by application of high heats and rapid coking, since to secure the high temperatures thereby required, producer gas—having a lower theoretical flame temperature than coke-oven gas—must be supplied at a rate higher than that corresponding to equal heat consumption per hour.

To make this point more clear, there is to be considered the progressive loss of heat from the burning gases to the oven and surroundings, and the more or less progressive character of the combustion, the heat not being instantaneously generated in its entirety at the burner. Due to this progressive loss of heat, the actual flame temperatures in the flues are much below the theoretical, actual measurements showing 2,000°-2,500° F. as against theoretical of 3,300°-4,100° F. Now, with gases of lower theoretical flame temperatures the rate of in-put of heat units must exceed that used with gases of higher flame temperatures, because it is necessary thus to render proportionately smaller the loss of heat to oven and surroundings, in relation to the total heat passing per unit of time. Then is the residual heat proportionately the same as that of the richer gases, per unit of the products of combustion, and

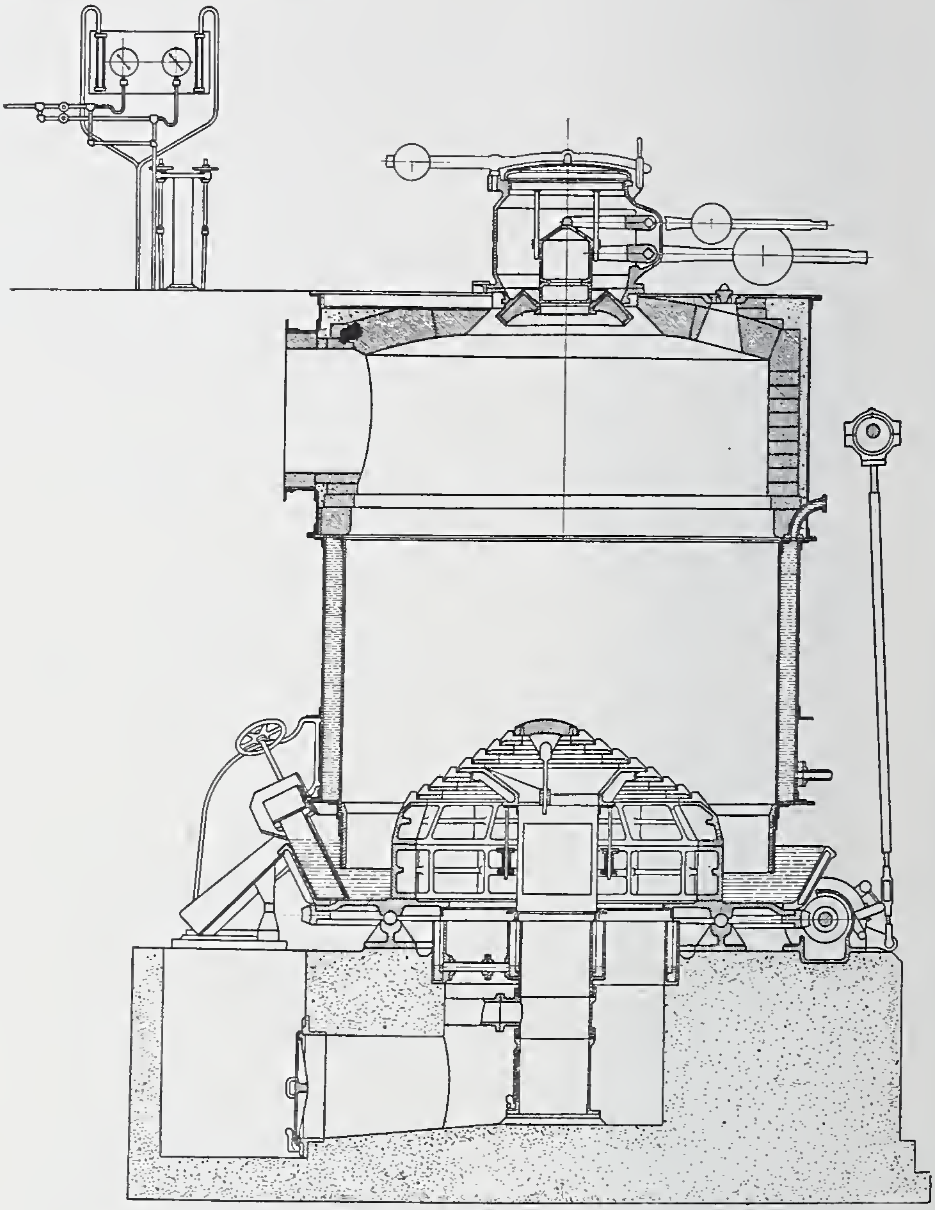

Fig. 110.—Koppers-Kerpely Gas Producer.

the temperature of the flues can be maintained at the degree required for rapid coking.

The increased loss of heat in waste gases (though the gases may be at lower temperatures) incurred by this high rate of burning is more than counterbalanced by the gains secured in the various other features of producer gas heating already enumerated.

Producer gas, if preheated, not only serves as well as coke oven gas for heating the ovens, giving equally well the high temperatures required for rapid coking, but as noted above (p. 267) it possesses certain advantages making it in many cases preferable, when outside demand exists for the coke oven gas. Greater uniformity of heating, readier control, and easier adaptability to a minimum of air excess, make for gains in efficiency—which, together with the added commercial values of surplus oven gas, outweigh ordinarily the necessary conversion loss in the producer and the somewhat excessive chimney loss.

The producers are fired ordinarily with the coke breeze and smaller sizes of coke, or coke breeze and a cheap grade of coal. The elimination of the smaller sizes in the coke output of the plant leaves the coke product, for furnace or foundry, improved in quality. Producers especially adapted to the use of finely-divided fuel, and having forced draft, ordinarily serve when coke breeze is used. One of these, the Kerpely, is illustrated in Figure 110.

The amount of fuel required in the producers commonly runs from 11 to 15 pounds per 100 pounds of coal coked. If the coke has a heating value of 12,000 B.t.u. per pound, the gross heat applied for coking is thus on an average 1,560 B.t.u. per pound of coal, which is an excessive amount as compared to heating by coke oven gas. About 15 to 20 per cent. of this heat is the loss incident to the conversion in the producer. Dust arresters or washers for the gas are required.

Data supplied by the Seaboard By-Product Coke Co., Jersey City, N. J., on the operation of their producer plant and two batteries Koppers ovens, 55 each, fired by producer gas, during the month of February, 1922, are given below (Table 33). Tables 34-35 are appended, taken from a report by W. Reed Morris, Ass't. Supt. of the Seaboard Plant, to the Carbonization Committee American Gas Association, 1922 (see Report of this Committee, pp. 37 and 39). These show operating data for the producers, each month from November, 1921, to May, 1922, inclusive, and a summary of heat distribution in the producer operation.

TABLE 33.

OPERATING DATA, SEABOARD BY-PRODUCT COKE CO., JERSEY CITY, N. J.

Two batteries of 55 ovens each, heated by producer gas, February, 1922.

110 Koppers Combination Type, Cross Regenerative Ovens, one battery (55) new July 31, 1917, one battery (55) new January 25, 1919.

Oven length (between doors)	37 feet 6 inches
" height	9 feet 10⅝ inches
" width	Tapers from 19½ inches to 17 inches
Average coking time, gross	19 hours 45 minutes
" " " net	19 hours 33 minutes

TABLE 33—*Continued.*

Coal Mixture, 75:25 high and low volatile; 80 per cent. through 1/8-inch screen; moisture content, 2.75 to 3.25 per cent.

Producers, six Koppers-Kerpely, capacity up to 50 tons per day; use small coke (domestic stove and nut); make total steam required by low pressure jacket surrounding producer; recover sensible heat of producer gas in high-pressure waste heat boilers.

Steam used in producer per hour per producer	1000 pounds at 5 lbs. gauge
Steam made in waste heat boiler: Average per pound dry coke used	.8 pounds at 150 lbs. gauge (or 1963 pounds per producer per hour)
Dry coke consumed in producer per ton coal coked	222 pounds (195 pounds carbon) (1439 B.t.u. per pound coal carbonized)
Producer gas consumed per pound coal carbonized	8.78 cubic feet (132.3 B.t.u., gross)
B.t.u. consumed (in gas) per pound coal coked	1150

TABLE 34.

HEAT DISTRIBUTION—SUMMARY.

	Item	B.t.u.'s on Basis of Average Day's Run	Per Cent. B.t.u. in Coke Used
Heat in	In coke used at producers	4,150,000,000	100
	Sensible heat air at 126° F.	21,500,000	...
	Heat in steam entering with air	141,500,000	...
		4,313,000,000	
Heat out recovered and used	Calorific value, gas	3,280,000,000	79.05
	High pressure steam made	314,000,000	7.57
		3,594,000,000	86.62
	Heat fed back into producer as sensible heat in air and into steam obtained from L. P. jacket	163,000,000	
Heat Loss Distribution	Excess low pressure steam made	7,000,000	.19
	Unburned carbon in producer ashes	45,700,000	1.10
	Unaccounted for producer losses — dust, radiation, etc.	49,200,000	1.18
	Boiler loss—blow down radiation, etc.	67,650,000	1.63
	Lost in scrubbers, cooling water, and radiation	385,650,000	9.28
		556,000,000	13.38
		4,313,000,000	100.00

TABLE 35.

AVERAGE OPERATING RESULTS.

Item	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	7 Months' Average
Coal carbonized—wet tons	1,427.4	1,510	1,585	1,620	1,320	1,481.5	1,601	1,506
Pound dry fuel/ton coal	225	216	236	222	224	220	234	225
Pounds carbon/ton coal	201	195	207	195	195	194	204	199
Daily gas make, M. cubic feet	25,100	25,600	28,300	28,000	23,300	24,900	29,000	26,310
Gas analysis per cent. CO_2	5.0	3.8	3.4	3.7	3.3	3.4	3.0	3.6
O_2	.3	.2	.1	.2	.2	.2	.1	.2
CO	27.4	29.4	30.2	29.8	30.4	30.7	30.7	29.8
H_2	11.1	10.2	10.4	10.1	9.7	9.7	9.5	10.1
CH_4	.4	.3	.3	.3	.3	.1	.2	.3
N_2	55.8	56.1	55.6	55.9	56.1	55.9	56.5	56.0
Gr. B.t.u.'s/cubic foot	128.5	131.4	134.6	132.3	132.8	131.9	132.3	131.9
B.t.u.'s/pound coal carbonized	1,132	1,112	1,200	1,150	1,170	1,105	1,200	1,153
Cold gas efficiency per cent	76.9	76.5	79.2	79.8	80.5	79	79	78.7

Whether, economically, the use of producer gas will pay, depends on the relative prices obtainable for B.t.u.'s in the form of oven-gas and coke. Cost of plant and cost of operation of the producers, of power and steam used, and of the screening of coke, must be weighed here against any gain from higher value of oven gas sold or any advantage in efficiency of producer gas heating.

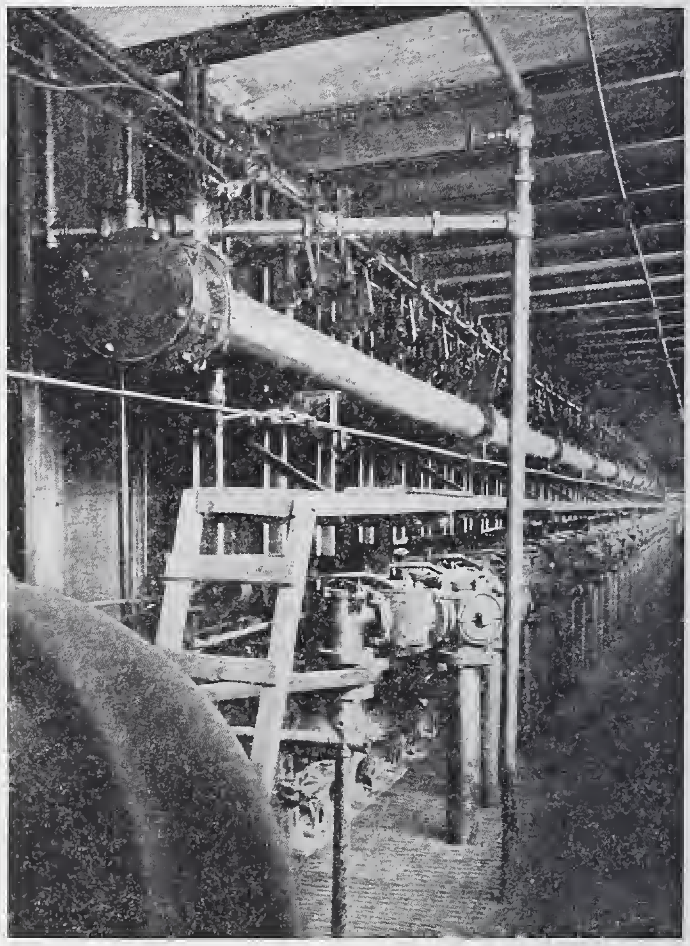

FIG. 111.—Arrangement of Under-bench Fittings, for Firing Koppers Coke Ovens with either Coke Oven Gas or Producer Gas (coke oven gas supply line above, producer gas lines below).

The double or two-compartment regenerator (or a system connecting alternate regenerators to fuel gas and air) as has been explained in another chapter (see pp. 201-2) is used when fuel gas as well as air is preheated. The hot waste gases pass through both regenerators in parallel, on their way to the stack, but on reversal a suitable arrangement of valves admits air to one and producer gas to the other (Figure 111, also see Figure 75, page 201). Both gas and air then, after being heated, enter the oven flues through the same ducts by which the waste gases in the preceding period had their exit.

The Use of Blast Furnace Gas.

Cleaned blast furnace gas is frequently available in large quantities for use in heating ovens located at steel plants. Its cost is low, or often can be set at a low figure based upon its fuel value as applied in the stoves of the blast furnace.

What has been said in the preceding paragraphs as to the use of producer gas applies in most respects equally to blast furnace gas. The latter has lower heating value and requires less air than producer gas. Unless a larger excess of air is used than with producer gas, making the volume of air more nearly equal to that of the gas (see Table 31), the air will not take its proper share of the heat of the regenerator through which it passes, and this chamber will not fully absorb the waste gas heat, resulting in loss.

The flame temperature accordingly, in Table 31 has been calculated as with 25 per cent. excess air in order more nearly to equalize the gas and air volumes and their heat-absorbing capacities. Too much air excess tends to lower unduly the flame temperature.

Study of the relative heat capacities of waste gases on the one hand and of fuel gas and air on the other, shows that when burning blast furnace gas with 25 per cent. excess air (see Table 31), these capacities (calculated for equal temperature ranges) are approximately equal, and therefore about an equal temperature change can take place, the air and gas being raised by 1,500°-1,600° F., provided there is approximately an equal drop in the temperature of the waste gases. A preheat of 1,700° F. can be obtained in the air and gas if the flue temperatures are high and the waste gases enter the regenerator at 2,200° F. or higher.

The Use of Blue Water Gas.

Blue water gas frequently can be used advantageously in heating ovens, particularly when the coke oven plant is contiguous to or part of a gas plant equipped with water gas generator sets. Coke from the ovens may be used as generator fuel. Water gas requires no preheating and is therefore especially adapted to use in the Semet-Solvay and other systems where the preheating of both gas and air is difficult.

By reference to Table 32 presenting the volume and heat relations in the combustion of water gas with preheated air it may be seen that a flame temperature higher than that with coke oven gas is theoretically possible. Caution must be used therefore in firing with this gas, particularly as its heat value per cubic foot (about one-half that of coke oven gas) may influence the heater to adopt an unsafe rate of burning.

The relative heat capacities of air (using 10 per cent. excess) and waste gases (see Table 32) over an equal temperature range, are about as 3 to 4, a ratio lower than in case of coke oven gas. This condition results either in a requirement of a larger air excess (thus lowering the flue temperature), or a relatively greater loss of waste heat to the chimney, due to the incapacity of the air to regenerate the same amount of the waste gas heat as in case of oven gas.

On account of the high flame temperature in the combustion of water gas with preheated air, and also the deficiency in heat capacity in the air as compared to the waste gas, the expedient of *waste gas return,* previously referred to, may be advantageously used, admitting either with the air or fuel gas, or both, a regulated amount of inert gases returned from the chimney. Such procedure would be particularly adapted to vertical flued ovens where the lengthening of flames and increased velocity thus secured is desirable. This expedient tends also to afford better control of temperature in the flues.

Both with blue gas and blast-furnace gas there is attained the advantage of freedom from clogged burners, from tar or soot deposited, and also in common with producer gas, these fuels afford a more even control of heats, due to their lean character.

Structural Features Affecting the Heating of By-Product Coke Ovens.

Mention has been made in another connection of the favor increasingly being accorded to the *narrower oven.* Capacity gained by increase of width fails, after a certain point, to increase economically the rate of output, owing to the difficulty of forcing the heat to the center of the charge when a greater width is used. Much depends upon the kind of coal to be used, and the quality of coke required, but in general it is now found that ovens between 11 inches and 16 inches in average width are in the long run most economical of operation. Increase of length to 40 feet and of height to 12 feet has been found to offer no serious difficulties as far as heating is concerned. The narrow oven and comparatively low flue temperatures have favorable effect on coke quality when using the high-volatile, higher-oxygen coals.

The taper in width of the oven, usually 2 inches or 2½ inches, requires especial provision for additional heat per square foot of wall area at the wider end (on coke discharge side). In the (old) Koppers type this is taken care of in the design by providing on the coke side a smaller number of vertical flues to carry the total amount of burning gases, thus insuring a greater amount of heat per flue.

Incidentally, it may be noted that herein a disadvantage attaches to the Koppers regenerative system (old type), in that the larger group of flues on one end, are provided with air regenerated from a relatively smaller quantity of waste gases (from the smaller group of flues at the other end). Some fluctuation of temperature thereby ensues in the waste gas to the chimney and in oven wall as between the periods of reversal and as between coke side and pusher side. (Figure 74, p. 200).

In vertical flued types which do not reverse, or in which the reversal is from one flue to its next adjoining neighbor, the regulation is at the individual burners. In the Semet-Solvay system such regulation (to take care of taper in width) is made by varying the openings in the burner inlets, as between those at the wide end and narrow end of the oven.

The New Type Koppers oven (Becker's patent) (see pp. 194-200) provides for such regulation by the use of different quantities of fuel in the various groups of flues—end to end of the oven. The disturbance (above noted) of the even regeneration of air in different sections does not therein appear.

Rate of heat penetration through the coal charge is not entirely a function of wall temperature and width of oven. It is affected by the nature of the coal, particularly by the oxygen content, and by the degree of fineness and the percentage of moisture in the coal. These things, therefore, as defined by the local conditions play a part in the design of ovens for any plant.

The control of *heats* in the *top space* above the coal charge, is essential to the securing of maximum yields and most desirable quality in by-products. The temperature of the tops is kept well below that of the main portion of the walls, but must be high enough so that the coking of the top layer of the charge is completed before the balance of the charge becomes overcoked. In ovens of the vertical-flued type, this condition is mainly secured by placing the common horizontal flue at the proper height in relation to the top of the coal charge (compare Figure 39, p. 144). In many of the more recent American installations the position of this flue is lower with respect to the coal than was previously considered advisable. The New Type Koppers oven, however, again raises it. In the Semet-Solvay (horizontal flue) type of heating wall, the top flue temperature can be controlled by variation of the fuel gas supply to the top burner. The height of the oven (and of the charge) in relation to the position of the topmost flue, affects in large measure, in any type of oven, the top temperatures.

The effect of *prevailing wind pressure* on control of heats in the ovens is a matter to be carefully taken into account. Not only is a cooling effect produced on the battery on its windward side, but chimney draft and air-inlets receive a direct pressure effect from the wind. Automatic stack draft control, to counteract this influence, is advised by some oven builders.

In *the first heating* of a *new battery* of ovens from the cold, the utmost precaution is needed to prevent distortion of oven walls and the opening up of leaks in the flues by uneven expansion. Silica brick, used now very generally in America for coke oven construction, expand approximately on an average, 3/16 inch per linear foot in heating to the working temperature of the modern oven. This expansion is allowed for by leaving spaces known as "expansion joints" (see p. 164), carefully predetermined as to size and proper placement between the brick when they are laid.

The "heating-up" period is generally from 6 to 12 weeks in length, on a silica battery; a shortening of this period involves great risk of damage to the brickwork. Wood fires are first built in the interior of each oven, the smoke and hot products passing out through a temporary opening in the wall of each oven into the heating flues. After heating slowly for a suitable period with the interior fires, fuel gas (ordinarily from a gas producer) is turned into the heating flues and its flow very gradually increased.

The tie-rods securing the battery structure are carefully adjusted during the heating-up period to allow for any expansion that may not be taken up in the expansion-joints.

Uniform Oven Pushing, and Its Effect on Heating Efficiency.

Hardly can too much emphasis be placed on the importance of regularity of oven operation, and its bearing on plant results in uniformity of heat conditions, quality of coke and life of the ovens. If a charge, for example, remains in the oven, say, 1 hour after coking is complete, due to irregular operation, or to uneven heats, just so much unnecessary fuel gas is burned in the flues, and heat economy is lowered. The flues also under such conditions are likely to become over-heated, and the coke may push with difficulty, straining the walls.

A schedule of pushing and charging ovens must be chosen with a view to regular operation, and rigidly adhered to. As has been brought out in another chapter (see pp. 154-5), the ideal pushing schedule is one which gives, in both of the ovens next adjacent to that being pushed, the greatest possible age since their time of charging. When this is attained (as in Marquard's schedule by odd numbered cycles, see pp. 156-8) the ages of the two adjacent ovens approach equality, at about half of the coking time.

It is readily apparent that, in those types of oven batteries where a single heating wall separates and heats two ovens, a condition detrimental to uniform heat transfer arises, if at the time any oven is recharged, its right hand neighbor (say) is very much riper or very much greener than its left hand neighbor. More heat is being taken by the greener oven and therefore the wall on that side will more slowly recover its normal temperature than will the one next to the riper oven. Irregular and non-uniform heating within that oven and as between various ovens necessarily results. (See p. 154, and Figure 45, for a graphic illustration of these conditions.)

Such irregularity is minimized when the oven ages on either side approach equality, and when throughout the plant the relative oven ages adjoining any oven being pushed are essentially the same.[11]

In respect to these influences and conditions the common practice at American coking plants of using a "10-cycle" in pushing (that is, pushing, say, all of the "ones," then all of the "fours," all of the "sevens," etc.), is likely to have injurious effects, since the disparity in ages between next adjacent ovens is irregular and generally large (see various schedules outlined, pp. 154-9). Dividing the battery into odd-numbered groups or cycles by Marquard's method is better practice if it can be adapted successfully to a simple daily routine.

Cardinal Points to Secure Efficiency in Heating.

For securing a practical maximum of economy in the heating of by-product coke ovens, manifested in a minimum use of fuel, the following rules may be briefly summarized:

(1) There must be *even distribution* of heat throughout the oven wall, so that the charge is uniformly coked in the minimum period reached by any portion.

(2) *Regularity of pushing schedule* with shortest practicable period of delays in regular operations of charging and discharging ovens; regularity also in coal mixture, its kind, degree of fineness and content of moisture.

(3) *Regulation of fuel gas* and *air* supply so that combustion is complete and the air excess is a practical minimum in the issuing gases.

(4) *Avoidance* of *unnecessary heats* at *the tops* of the ovens, which causes needless radiation loss and discharge of heat in the oven gases.

(5) Careful and *regular cleaning* of *gas inlet nozzles.*

(6) Control of *chimney draft,* automatically if possible.

(7) Systematic *attention* to *repair of leaks* (particularly about the oven doors and jamb bricks) which cause cooling of the oven ends and introduction of excess air into the flues.

(8) Control of *oven pressure* or *suction* to avoid drawing flue gases through oven walls into oven.

(9) Maintaining a *minimum* of *pressure-drop* in the *heating flues,* to avoid drawing oven gases through the walls.

(10) *Recuperation* of *the heat* of the battery *brickwork* so as to preheat the cold air drawn to the regenerators.

(11) *Design* of *regenerators,* as to relative size and the manner of laying of the checquer brick fillings.

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[11] The detail of these relationships and of the mathematical derivation of the most advantageous pushing schedule is developed clearly and instructively in U. S. Pat. 1,323,711, of W. B. Marquard, elsewhere referred to.

Chapter 11.

The Recovery of By-Products in Coal Carbonization.

General. The by-products usually recovered from coal carbonization in by-product coke ovens, gas retorts, and low-temperature retorts, are gas, tar, ammonia liquor, ammonium sulphate, and light oil (often called "benzols"). There may be recovered also cyanides and sulphur, although in America, owing to commercial conditions (competition from other sources, etc.) these recoveries usually are not found profitable and are neglected.

Many secondary by-products are obtained, at separate plants, from the tar and light oil, but their listing, and an account of their manufacture, forms a large subject, outside the scope of this work.

The Make-up of the Foul Gas. As the so-called "foul gas" leaves the outlet of oven or retort, it is made up of the permanent gases, whose mixture forms the final purified "coal gas" for the market, and, accompanying it, mixed, or in suspension, the vapors of water, tar and light oils, with solid particles of coal dust, heavy hydrocarbons, "carbon" or carbon nuclei, and complex carbon compounds. These solid and liquid portions and the condensable vapors constitute, as the volatile products leave the oven, almost as great a proportion thereof, by weight, as the permanent gases.

Water, while not regarded as a by-product, is produced by the decomposition of the coal, and appears in the ammonia liquor. In amount, including the free moisture of the coal, it may exceed that of the tar, and reach 7 per cent. or more of the coal charged, if certain grades of high-volatile coals or coal mixtures are used.

Summary of the Process. The apparatus used for cooling the gas and recovering from it the by-products varies in kind among the different oven systems and as between the high-temperature carbonizing systems, and the low temperature. In the latter both the quality and quantity of the by-products are materially different from those of the former, and recovery apparatus has to be designed accordingly. In general principles, however, all plants are much the same. Drips and condensates appear first in the large air-cooled mains (one-half to two-thirds of the tar and much of the liquor being removed here), the gas is then cooled by water in so-called primary coolers, passed through mechanical exhausters (which remove some tar), tar extractors for removing the last of the tar mist, ammonia scrubbers (washing with water) or saturators (washing with acid and forming sulphate), final coolers, and absorbers or washers for light oil vapors using a heavy washing oil.

The rate at which the gas is cooled was at one time held to have an important influence on the quality of the final cleaned gas, in respect to its content of the vapors of condensable hydrocarbons. Modern views (and practice) place greater stress on the influence of relative amount of contact of the gas with the condensates, and the temperature of the latter. Since the liquid and condensable material remaining in the gas as it leaves the collecting main is very finely divided, and dispersed in relatively a large volume of gas, there is required large and well-designed apparatus for its effective removal. Cooling, mechanical impingement, and the direct scrubbing action of water and absorbent oils, are the means employed.

In the design of condensing and cooling apparatus, the "saturation temperature" of the gas at the inlet of the condenser is the important determining factor. In other words, the temperature at which the particular average gas under treatment becomes saturated with respect to its condensable ingredients, enables the designer to estimate the quantity of heat to be extracted. The latent heat of condensable vapors is, at this point, very much in excess of the sensible heat of the gas.[1]

Tar and aqueous liquor drop out together when the gas is cooled. The liquor dissolves some ammonia and ammonium chloride (with lesser quantities of hydrogen sulphide, carbonic acid, etc.). If it is kept as cool as possible and the less concentrated portions constantly circulated in the mains to meet the higher concentrations in the gas, a considerable portion of the ammonia in the gas is dissolved. If, however, the liquor is allowed to become hot and the stronger portions only to have contact with the gas, the vapor pressure relationships of ammonia in liquor and gas cause the larger part of the free NH_3 to to pass on with the gas, for subsequent recovery in the saturators. Fixed ammonia is in any case largely dissolved by the liquor condensing in the mains.

Tar also, in a gaseous carrying medium, of relatively so large a volume, and in the form of mist, very finely divided, requires careful coördination of temperature control and mechanical treatment to effect its complete removal. This must be accomplished in advance of the ammonia saturators, to avoid contamination of the product of ammonium sulphate. The balance between a maximum of tar removal and a minimum of ammonia separation—in advance of the saturators—by cooling and solution, has constituted a problem that has taxed the ingenuity of the designers of apparatus.

Whether ammonia is to be recovered largely as its aqueous solution —ammonia liquor—or as the fixed salt ammonium sulphate, by direct

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[1] See Report of the 1923 Committee on Fundamentals of Condensing and Scrubbing, American Gas Association, W. H. Earle, Chairman, pp. 1 and 2.

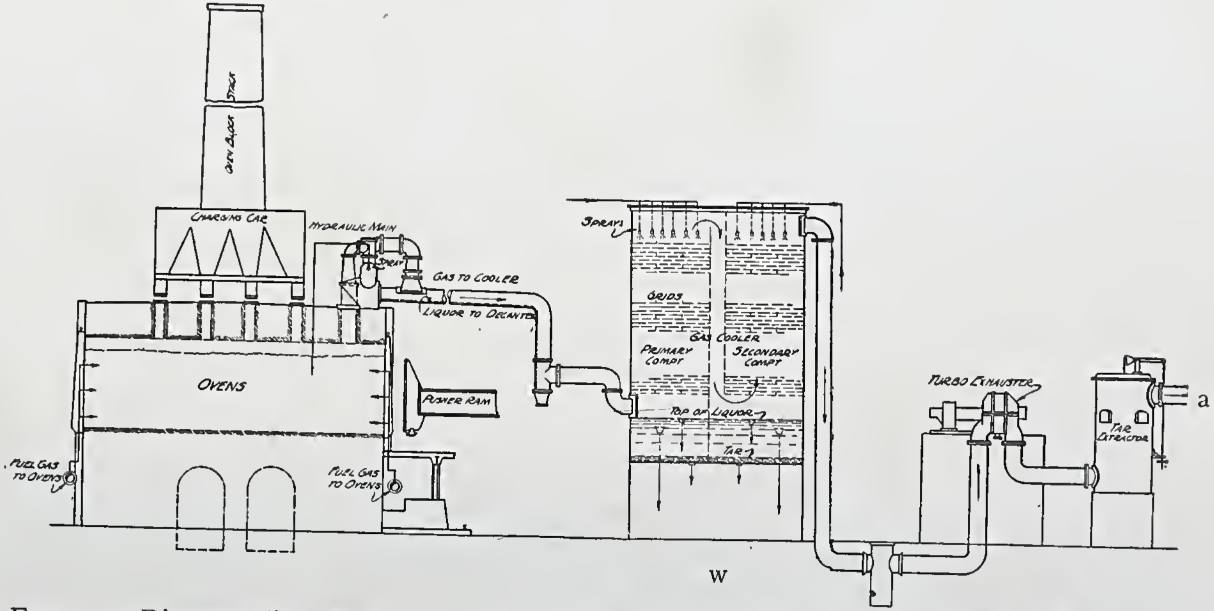

FIG. 113.—Diagram (in Elevation) of By-Product Recovery Apparatus and Gas Flow System, Using Direct Recovery of Ammonia as Sulphate (drawing furnished by Semet-Solvay Co.) —(continued on next page).

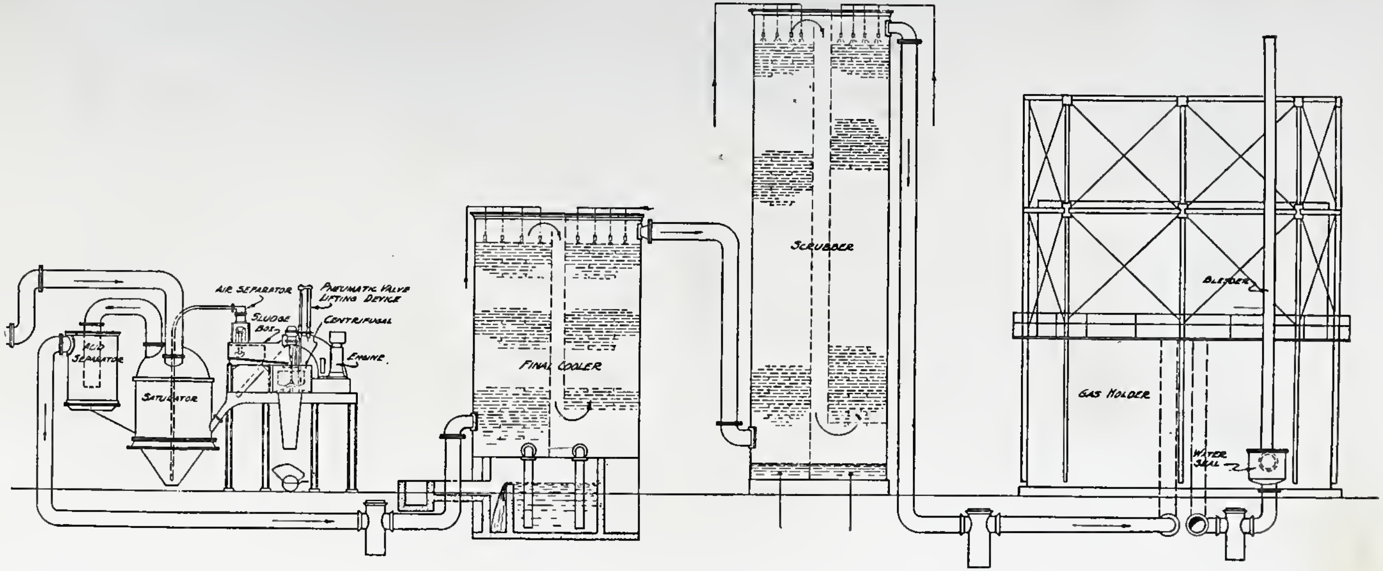

FIG. 113a.—Diagram (in Elevation) of By-Product Recovery Apparatus and Gas Flow System, Using Direct Recovery of Ammonia as Sulphate (drawing furnished by Semet-Solvay Co.)—(continued from preceding page).

action of sulphuric acid on the gas, affords the controlling factor in the arrangement and design of the by-product recovery system.

Diagrams illustrating the gas flow in the two systems are given in Figures 112, 113 and 113a.

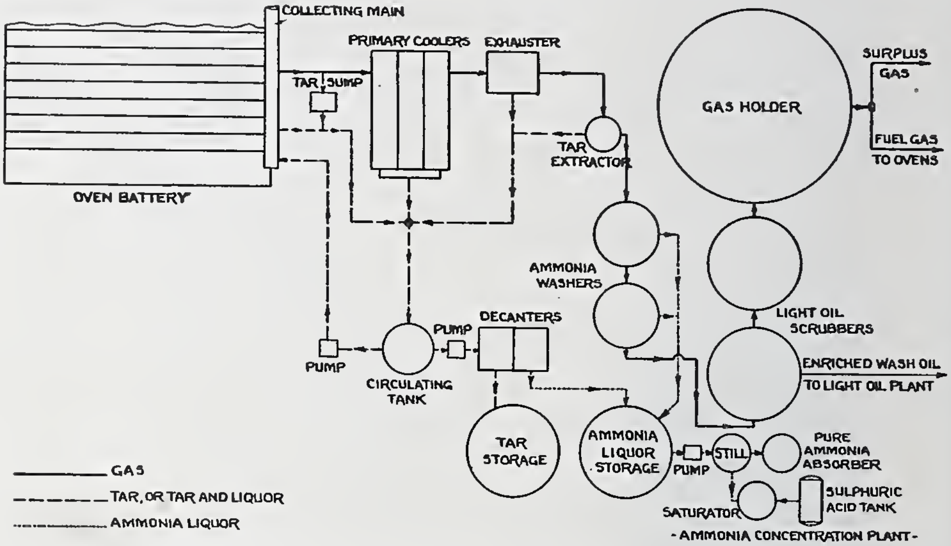

FIG. 112.—Flow Chart of By-Product Recovery System (diagrammatic), with Recovery of Ammonia as Liquor or Indirectly as Sulphate.

Apparatus and Processes

Collecting Main and Suction Mains. These mains and the control of pressure therein as affecting oven operation have been described in a preceding chapter. The collecting main, transversely placed over the ovens (Figure 114), at, usually, their pusher-side end, receives the "foul gas" through up-takes, one from each oven entering its side or top. These pipes, in by-product coke oven practice, do not dip under the surface of the liquor in the main. In gas retort plants they frequently do, in order to form a seal at each retort, necessary during charging. The latter type of main is what is known as a "wet" or "hydraulic" main.

A mixture of tar and liquor from the drain tanks of the condensing system, is pumped back into the collecting main, for flushing out the tar and pitch which are immediately formed on the first cooling of the gas. The proportions of tar and liquor in this flushing mixture vary according to conditions. Often a mixture carrying 60 per cent. liquor and 40 per cent. tar is used. In some plants this flushing is carried out through liquor sprays at or near the gas inlets, which practice tends to prevent pitching of the valve seats. The recirculation, through the main, of tar drawn from the coolers and tar extractors helps in redistilling therefrom, by the hot gases, the light oils for final recovery in the light oil absorbers.

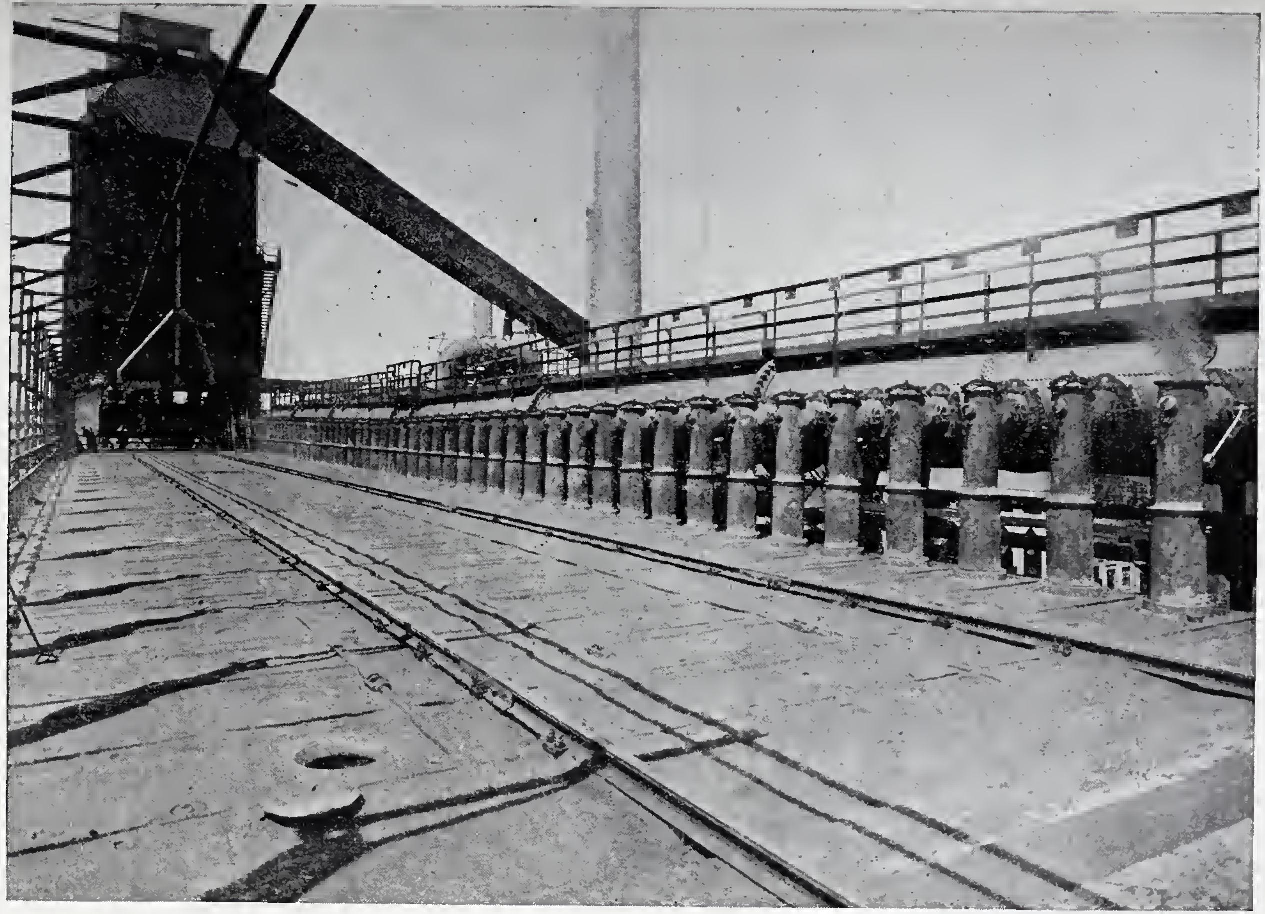

Fig. 114.—Top of Oven Battery, showing Up-take Pipes and Collecting Main (Koppers Ovens).

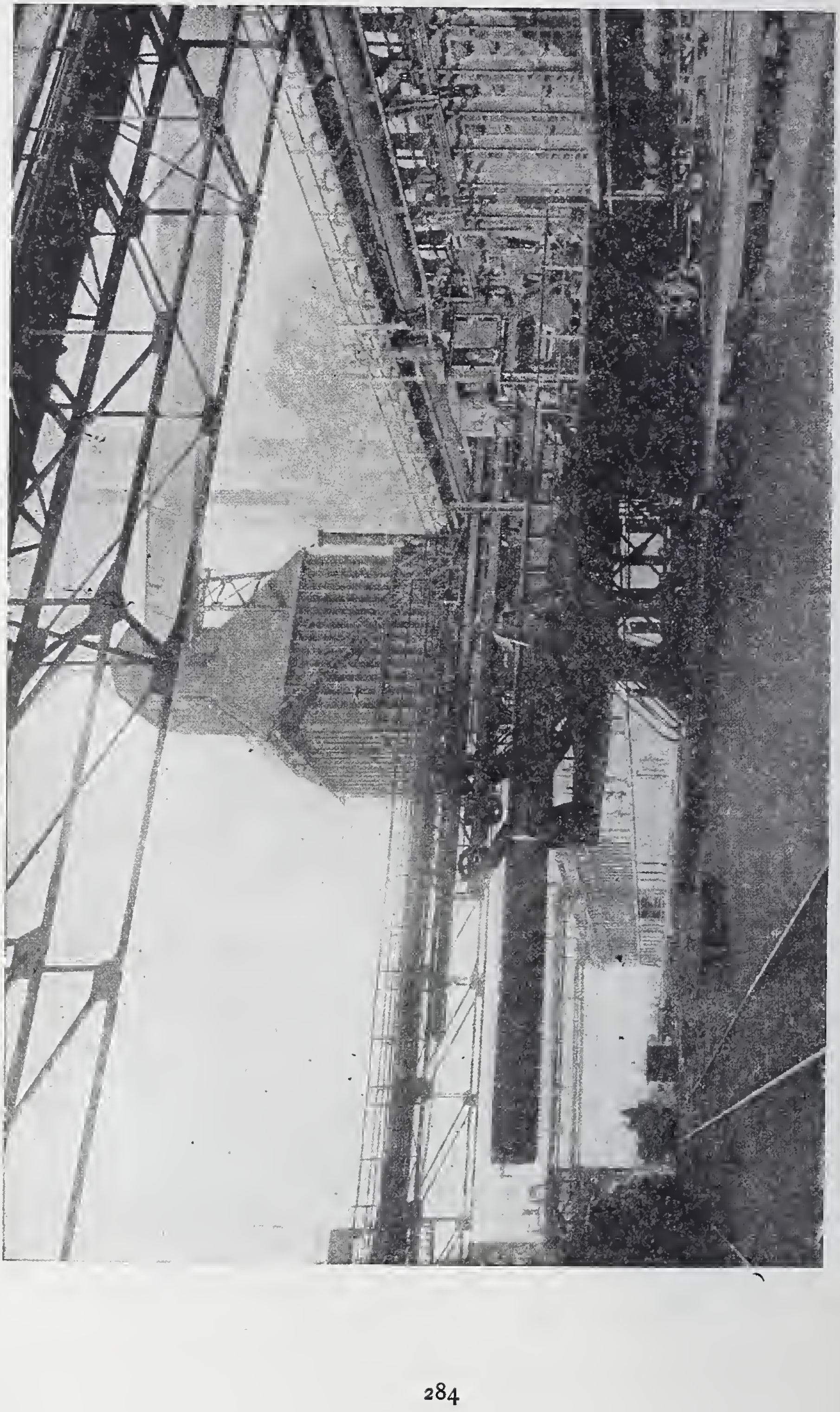

Fig. 115.—View of Oven Batteries, showing Collecting Main and Four Cross-over or Suction Mains (pusher machine in foreground).

Pitch traps in the base of the collecting main, usually at the ends, allow the spooning out or removal of heavy pitch by a suitable tool.

A regulated pressure of 2¾ to 3½ mm. of water (closely controlled by governors, as has been described) is maintained in the collecting mains, this condition establishing practically even pressure in the ovens.

The suction or cross-over mains carry the gas over from the collecting main to the by-product recovery apparatus at some distance from the oven or retort battery. They are several in number depending on the size of the plant (Figure 115). Before entering the coolers these mains unite and are drained into a sump, or *tar seal tank,* which collects the condensate formed along the way by air-cooling. The gas enters the suction mains at 130°-150° C. (266°-302° F.).

Tar and liquor returned from the flushing of the mains, and the excess from the coolers, seal tanks and other collecting points, is pumped to the *tar separation tank* or *decanter,* a tank provided with one or more vertical partitions, and filled in such manner that the tar and aqueous ammonia liquor separate roughly by gravity. The tar being of specific gravity 1.15 to 1.20 sinks to the bottom.

The many pumps required for flushing of the mains, transfer of tar and liquor to storage, loading of tar into cars, the circulating of cooling water, etc., are assembled largely in one pump room for convenience. Tar pumps are now generally motor-driven centrifugals, although for some purposes, as tar loading, the steam-driven piston pumps are often preferred. Live steam connections for clearing tar and pitch stoppages are freely provided.

Primary Coolers. At a temperature of about 75° C. (167° F.) the gas passes from the suction mains into the primary coolers. These stand usually outside of the by-product building (Figures 116 and 117). A very common form is the indirect type wherein the gas passes upward in a shell around vertical rows of pipes carrying the cooling water in counter direction to that of the gas. There are several vertical passes of the gas, in series, arranged by baffles.

The gas temperature is reduced in these coolers to 28°-30° C. (82°-86° F.). Automatic regulators of the flow of cooling water may be used.

The Semet-Solvay, and less generally other, systems, especially in those plants making ammonia liquor instead of sulphate, uses a direct, water spray, wooden grid, type of cooler, called the washer-cooler (illustrated at w, Figure 113), the gas travelling vertically, in two or more passes, in direct contact with water or weak-liquor sprays descending over wooden grids.

This is a simple and efficient type of scrubbing or cooling apparatus much used in the modern plant for either cooling or cleaning the gas or extracting ammonia or light oils. Its use has in large measure replaced more complicated and expensive washers commonly deemed necessary in the older plants. The cooling medium comes in direct

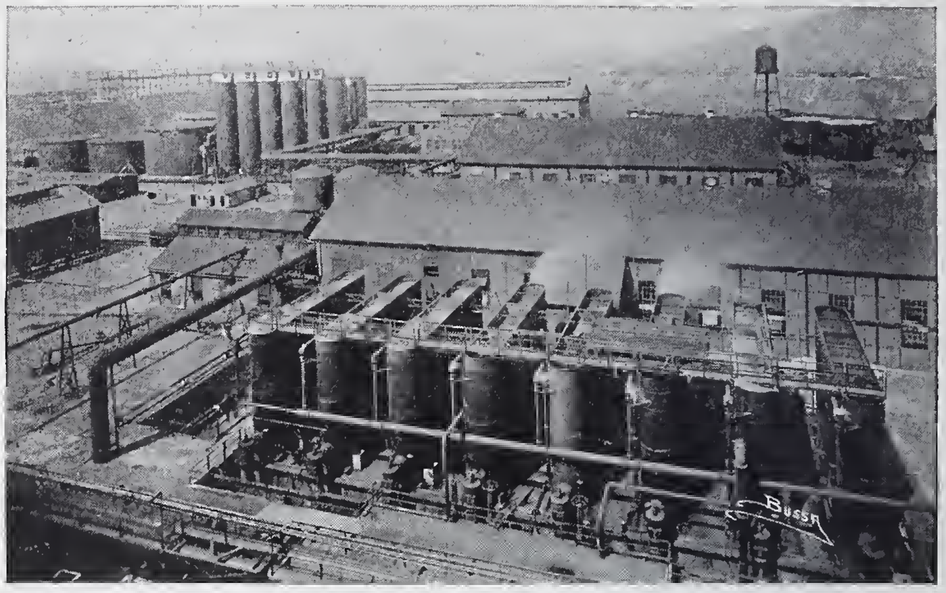

Fig. 116.—General View of Primary Coolers and By-Product Buildings, with Final Coolers and Benzol Absorbers Seen in Distance on Left Center.

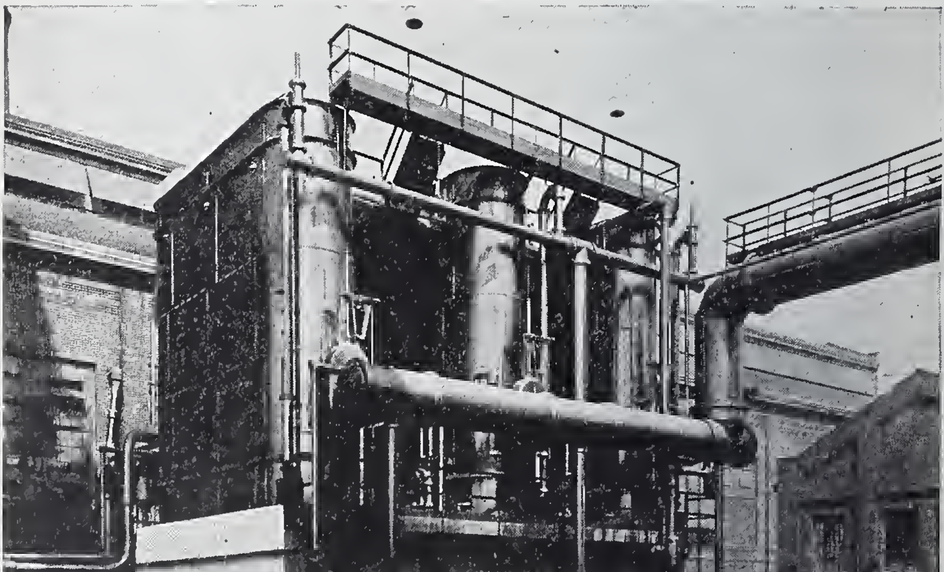

Fig. 117.—Primary Coolers, outside of By-Product Building.

contact with the gas to be cooled, and the intervening metal walls of the indirect type are thus dispensed with. For transfer of heat, from gas to liquid, a large gain in efficiency thereby results.

The cooling medium, if it is to be recirculated, must itself be cooled again, in outside coils over which cold water is sprayed or in jacketed-pipe coolers. The heat transfer here is from liquid to liquid in which case there is less hindrance to conduction through the metal containing-wall than when moving gases are being cooled and highly resistant films adhere to the cooling surfaces. (The principles of cooling and condensation as applying to these operations are ably presented by W. H. McAdams and T. H. Frost, in Industrial and Engineering Chemistry, vol. 14 (1922), p. 13, and by W. K. Lewis and W. H. McAdams, American Gas Association, 1923, in a paper before the Technical Section, on "Factors in the Design of Absorption Apparatus.")

Exhausters. In order to overcome the resistance of the by-product apparatus and piping, the gas is drawn through the mains and primary coolers by exhausters or pumps, placed in the train of apparatus just beyond the primary coolers. Two principal types of exhauster are used, (1) the Connersville, or Roots, low speed, positive type, in which, at each revolution of the interior rotors a gas volume equal to the cubical content of the machine is driven through, and (2) the turbo-blower, high-speed type, in which the gas is given a rapid centrifugal motion by the blades of the rotating element, moving with suitable clearance within its casing.

The Connersville type of exhauster (Figure 118) is generally driven by direct-connected steam engine. It occupies more space than the centrifugal type, but is efficient and reliable over a wide range of capacities. The Clairton (Pa.) by-product coke plant of the Carnegie Steel Co., uses five of these exhausters (not including extensions under construction in 1923), each having a capacity of 40,000,000 cubic feet of gas per 24 hours, at 100 revolutions per minute.

The turbo or centrifugal exhausters (Figure 119) are in use at many of the newer plants. They have the advantage of requiring little space, being driven by direct-connected electric motor or steam turbine. This type has a further advantage, in that it serves as an auxiliary tar extractor, the high speed swirling motion imparted to the gas driving the tar particles against the outer casing and agglomerating them. Roughly 75 per cent. of the tar remaining in the gas after the primary coolers is, as a rule, removed by these exhausters.

The pressure change created by the exhausters may amount to 65 or 70 inches of water, or in other words, it may rise from a suction of 10-15 inches on the inlet side, to a pressure of 50-55 inches on the outlet side.

The compression thus produced in the gas raises its temperature by 15-20 degrees C., that is, from 30° C. to 45° or 50° C. This heat is sometimes removed by secondary coolers, especially if washers are to follow in which ammonia liquor is made. But in the majority

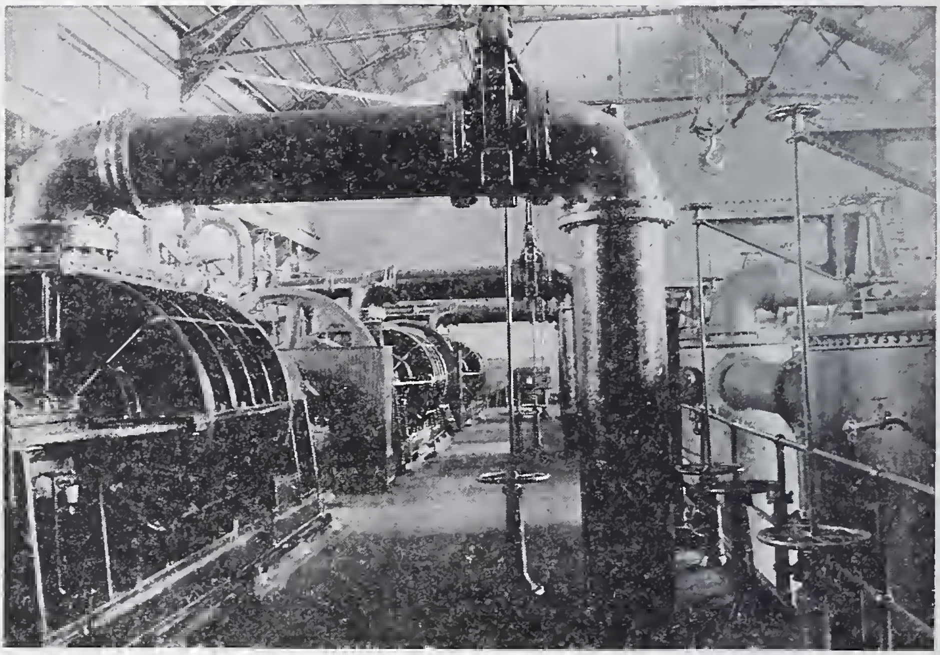

FIG. 118.—Connersville Type of Gas Exhausters.

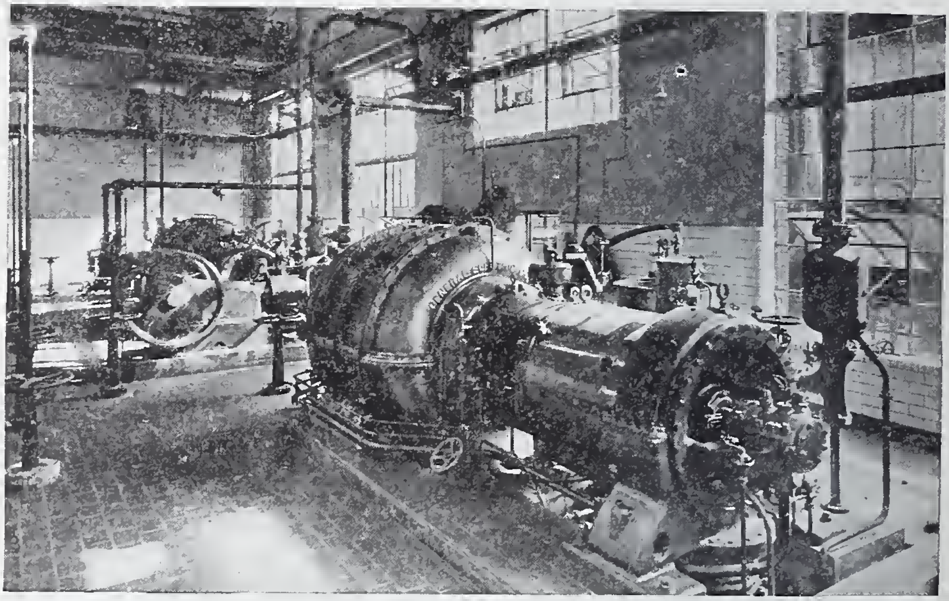

FIG. 119.—Centrifugal or Turbo-Exhausters.

of the more modern plants these are dispensed with and the heat dissipated in the ammonia saturators or washer coolers.

Tar Extractors. Following the exhausters the gas is forced, under pressure, through tar extractors, of which principally one type (the Pelouze and Audouin, or "P. & A.") is in common use. These throw out the fine tar mist, by the coagulating effect of impingement of jets of gas against surfaces. The gas passes through the perforations in the wall of an inverted drum or bell, against a similar drum within, whose perforations are staggered with those of the outer drum so as to cause impingement of the gas streams and of the tar particles that they hold in suspension, against solid surfaces.

The efficiency of these extractors is affected by the size of the perforations, the distance between the plates, the pressure differential and the temperature of the gas. For the latter, 43° to 48° C. (110°-119° F.) generally gives best efficiency. The pressure differential often is controlled by automatic regulator.

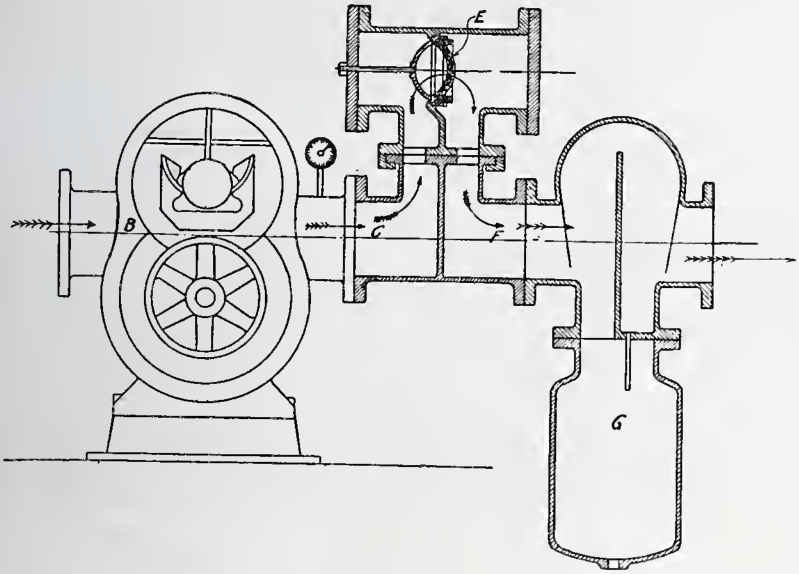

Fig. 120.—Diagram of Smith Type of Tar Extractor.

Another type of tar extractor finds wide application in cleaning producer gas, and has been used also successfully under some conditions for coke oven gas. This is the extractor employing a mat or diaphragm of glass wool in the path of the gas, against and through which the gas is driven under pressure, the tar fog being thus agglomerated into large drops. These do not accumulate on the mat, but drop out in a trap following the diaphragm. A diagram of this apparatus is shown in Figure 120, B being the exhauster, E the mat, and G the tar collecting trap.

Saturators, for Ammonium Sulphate. The gas on leaving the tar extractors is clean, practically free of tar and other suspended matter, and is at a temperature of 35°-40° C. (95°-104° F.). It carries three-quarters of the ammonia and 95 per cent. of the light oil vapors originally in the gas leaving the oven. It carries less than the saturation quantity of water vapor, having deposited a portion thereof by cooling to 30° C. in the primary coolers.

Before entering the saturators where ammonia is to be absorbed by strong sulphuric acid, with formation of solid, crystalline ammonium sulphate, the gas undergoes further treatment, to secure a suitable temperature and moisture concentration. The Semet-Solvay system passes it through an *"economizer"* wherein it is washed with the warm liquor from the hydraulic main, extracting the free ammonia and some moisture vapor therefrom, and being raised a few degrees in temperature. The Koppers system interposes a *"reheater,"* which by indirect heating with exhaust steam, raises the gas temperature to 50°-55° C. (122°-131° F.), but imparts no moisture vapor or ammonia.

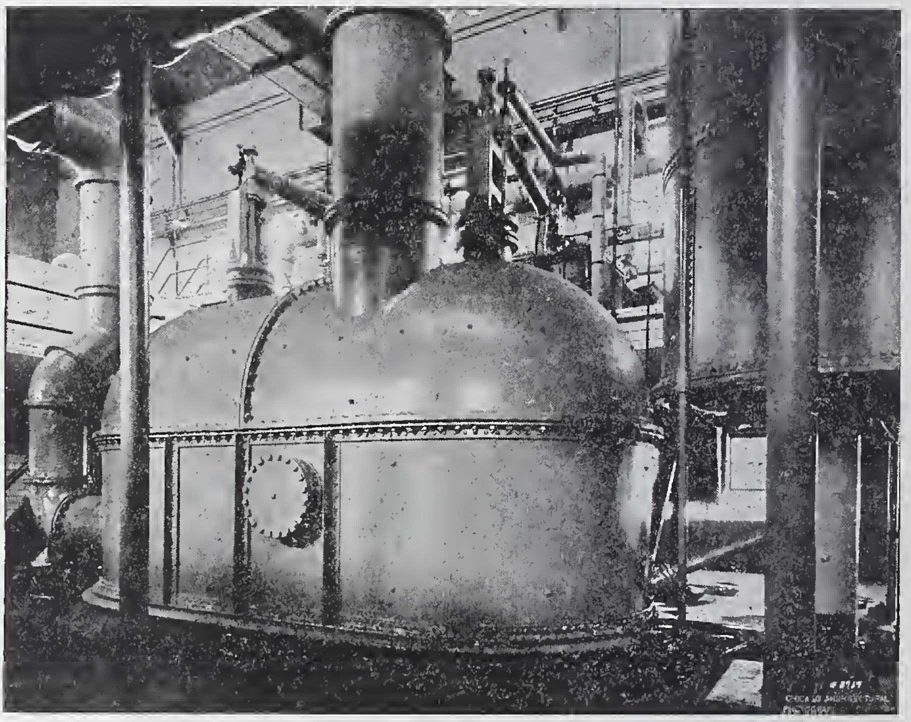

FIG. 121.—Saturator for Ammonium Sulphate, Koppers Type.

Ordinarily acid of 60° Baumé is used in the saturator. A continuous addition of this acid, regulated by frequent tests of the mother liquor, maintains the strength of the latter at 5-10 per cent. sulphuric acid, a condition proven most advantageous in obtaining high-grade sulphate. When the bath approaches neutrality or becomes alkaline, a blue or green color in the salt is likely to arise from the formation of ferro-cyanides. A slight amount of tar in the gas may produce a grey or brown color in the salt.

The heat of reaction raises the temperature of the bath. Moisture is thereby evaporated and carried on with the gas. If this evaporation exceeds in rate that of the inflow of water with the gas and in the acid, a concentration of the mother liquor takes place which increases the difficulty of handling the salt and renders it impure. The temperature of the bath, furthermore, has marked effect on the physical condition of the sulphate crystals.

The importance therefore of regulating the temperature and moisture content of the gas entering the saturator is readily to be seen. Sufficient heat must be imparted to the bath to maintain, with the aid of the heat of reacion, a temperature and concentration suited to the best formation of sulphate crystals—of a size and shape to be easily separated from their mother liquor in the centrifugal driers, and to yield thus a product of maximum purity.

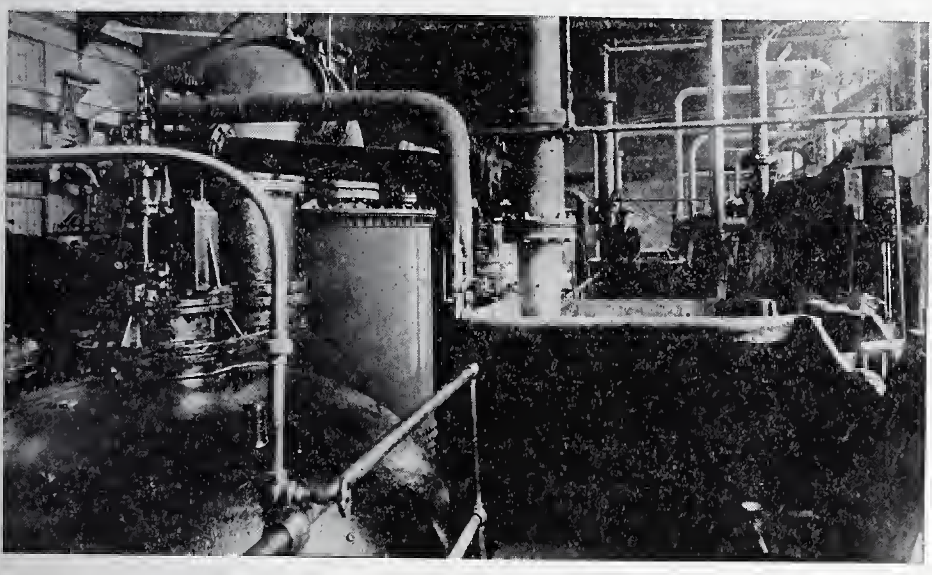

Fig. 122.—View of Top of Saturator, showing Drain Table for "Salt."

A saturator temperature of 60° C. (140° F.) is very commonly used with good results.

A stronger acid (66° Baumé) is sometimes used and the reheater preceding the saturator dispensed with.

The saturator (see Figures 121 and 122) is a heavily lead-lined and covered vessel holding the acid bath, under the surface of which dip the serrated edges of the "cracker" pipe through which the gas obtains intimate contact with the acid liquor.

The gas leaves the vessel through an acid separator, which takes out the spray mechanically carried over. The salt is removed from the bottom of the saturator by an ejector operated by compressed air, and falls upon a draining table (shown in Figure 122), from which the mother liquor is carried back into the saturator. The sulphate is then dried on centrifugal driers, whirling at 650 R. P. M., washed with a limited spray of water in the basket, and again whizzed till moisture is reduced to 2.0 per cent. or less. In some cases further drying is found necessary, in order to meet specifications, and is accomplished in a revolving drum hot air drier.

Ammonium sulphate as thus produced is white or light grey in color, contains 0.2 per cent. to 2.0 per cent. moisture, 0.15 to .50 per cent. free acid, and not less than 25.0 per cent. NH_3.

Ammonia Washers. The ammonia remaining in the gas after passing the tar extractors may, if desired, be washed out with cold water and made into ammonia liquor. In this case a secondary cooler and ammonia washers or scrubbers are used. Of the latter principally three different types are now in use:

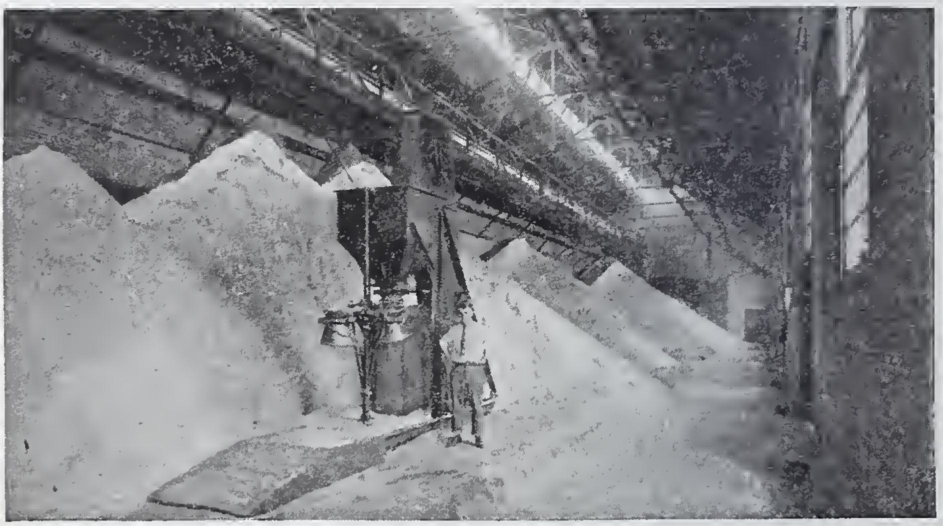

FIG. 123.—Ammonium Sulphate Storage at By-Product Coke Plant, showing Bagging Machine.

(1) The bell washer (exterior view in Figure 124), a tower made up of a series of sections superimposed, each of which consists of a tray containing liquor and a bell with serrated edges under which the gas, passing upward, bubbles through the liquor; the liquor flows downward from section to section through overflow pipes, leading, either within or outside of the tower, from the liquor surface in one section to that in the next.

(2) The direct-acting washer-cooler (previously referred to), a simple shell in which a water spray descends over wooden grids and meets the gas in counter current. This washer may be arranged as a so-called "intensive scrubber" wherein the gas passes upward suc-

cessively through a number of compartments, side by side, in a rectangular shell. The liquor circulation in each compartment is separate and distinct, except that the chambers in the bottom are connected by overflows and the separating weirs are of gradually decreasing height so that the liquor flows from one to another toward the gas inlet.

(3) The rotary scrubber, wherein the gas, instead of bubbling directly through the liquor, passes through a space in which large fresh surfaces of washing liquor are being constantly turned up by vanes or brushes on a rotating shaft. These scrubbers have a very large capacity owing to the large area of wetted surface exposed per unit of gas volume passing through per minute. They have an inherent disadvantage, however, in that they present in the liquor adhering to the rotating brushes a decreasing absorptive power during the period of the revolution, so that ammonia in the gas is likely to escape absorption during a fraction of the period.

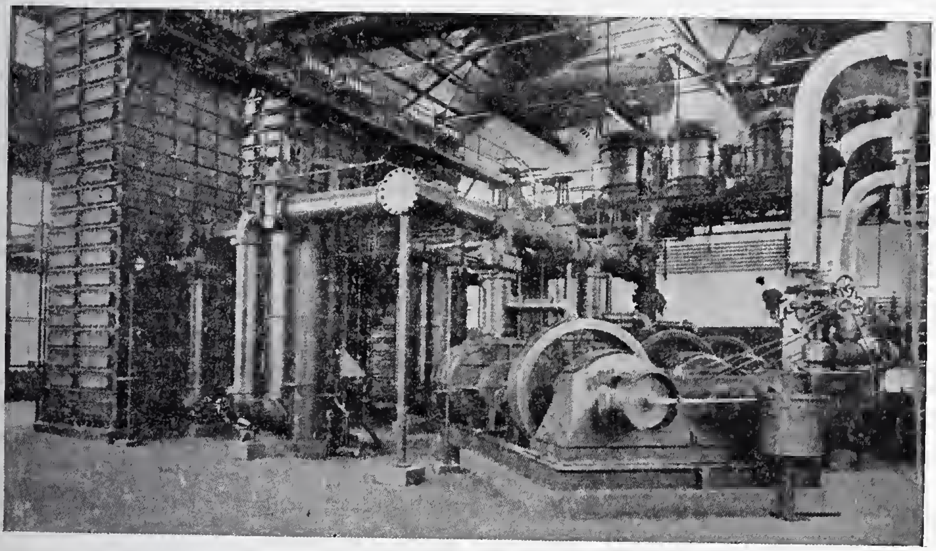

Fig. 124.—Ammonia Washers (on left), and Gas Exhausters with Steam Engine Drive in Foreground.

Ammonia Distilling and Concentrating Plant. The ammonia liquor obtained by condensation in the mains and primary coolers, as well as that from the washers, is of a strength approximately 1.0 to 1.5 per cent. NH_3, and must be distilled so as to deliver its ammonia content into the saturator, or concentrated so as to be economically shipped and marketed. A large part of its ammonia, furthermore, is held in the "fixed" form as chloride, sulphocyanide and other salts, which must be broken up by alkali,—in practice, milk of lime.

The ammonia still, in its simpler form, is a column made up of superimposed sections (see Figure 125) somewhat similar in general arrangement to that of the bell washers. It is a continuously operated still. The crude weak liquor flows downward from one section to another, and is heated as it descends by the steam and hot gases arising from the hotter sections below.

There is usually a preheater at the top of the still, in which, in order to drive off a part of the impurities of CO_2 and H_2S, the weak liquor is heated by steam coils to about 90° C., at which temperature a large part of the CO_2 and H_2S are driven off, together with some ammonia. The latter is absorbed in cold water and returned to the still.

As the liquor flows down through the sections of the main column, called the "volatile" still, and becomes further heated as above described, it loses most of its free ammonia. At the bottom is the so-called "lime-leg" into which milk of lime is introduced from the lime mixer and thoroughly mixed with the liquor by live steam. From the lime leg the mixture overflows into a shorter column alongside called the "fixed still." This is made up similarly of sections, downward through which the mixture of liquor and lime flows and is heated by live steam. The waste liquor flows out from the bottom of this still containing usually not over .005 to .010 per cent. NH_3.

The hot gases and steam arising from the top of the still pass through a dephlegmator removing most of the water and then into the saturator or to absorbers and purifying apparatus for making strong liquor.

For making crude concentrated liquor of 15 to 18 per cent. NH_3 for the market, the weak liquor, as it enters the top sections, is first deprived of part of its content of CO_2 and H_2S, as above described, by preheating. The liquor then passes to the still, the ammonia is driven out by steam as above described, and the vapors are led through the dephlegmator, which is in effect a partial cooler, capable of regulation by temperature control, so as to throw back into the still more or less of the water vapor as required, and thus yield from the final condenser any strength of ammonia liquor desired.

For the manufacture of pure aqua ammonia elaborate apparatus is required (Figures 127-128), consisting of dephlegmators, water washers, lime washers, oil, caustic, and charcoal washers, and finally absorption in distilled water. A detailed description of the ammonia concentration and purification plant and its operation leads apart from the subject of coal carbonization and the reader is referred thereon to articles treating especially of this subject.[2]

Final Coolers. On leaving the saturators the gas is at a temperature of 55°-60° C. (131°-140° F.), and requires cooling before an efficient recovery of the light oil vapors may be effected by scrubbing. The final cooler is of the direct-contact washer-cooler type in which a spray of water descends over wooden grids. The gas is cooled therein to 25° C. (77° F.) or lower if a supply of sufficiently cold

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[2] R. W. Hilgenstock, *Journal für Gas-beleuchtung,* 58, 709-14 (1915); C. C. Tutwiler, *Jour. of the Franklin Institute,* 1914, pp. 383-415.

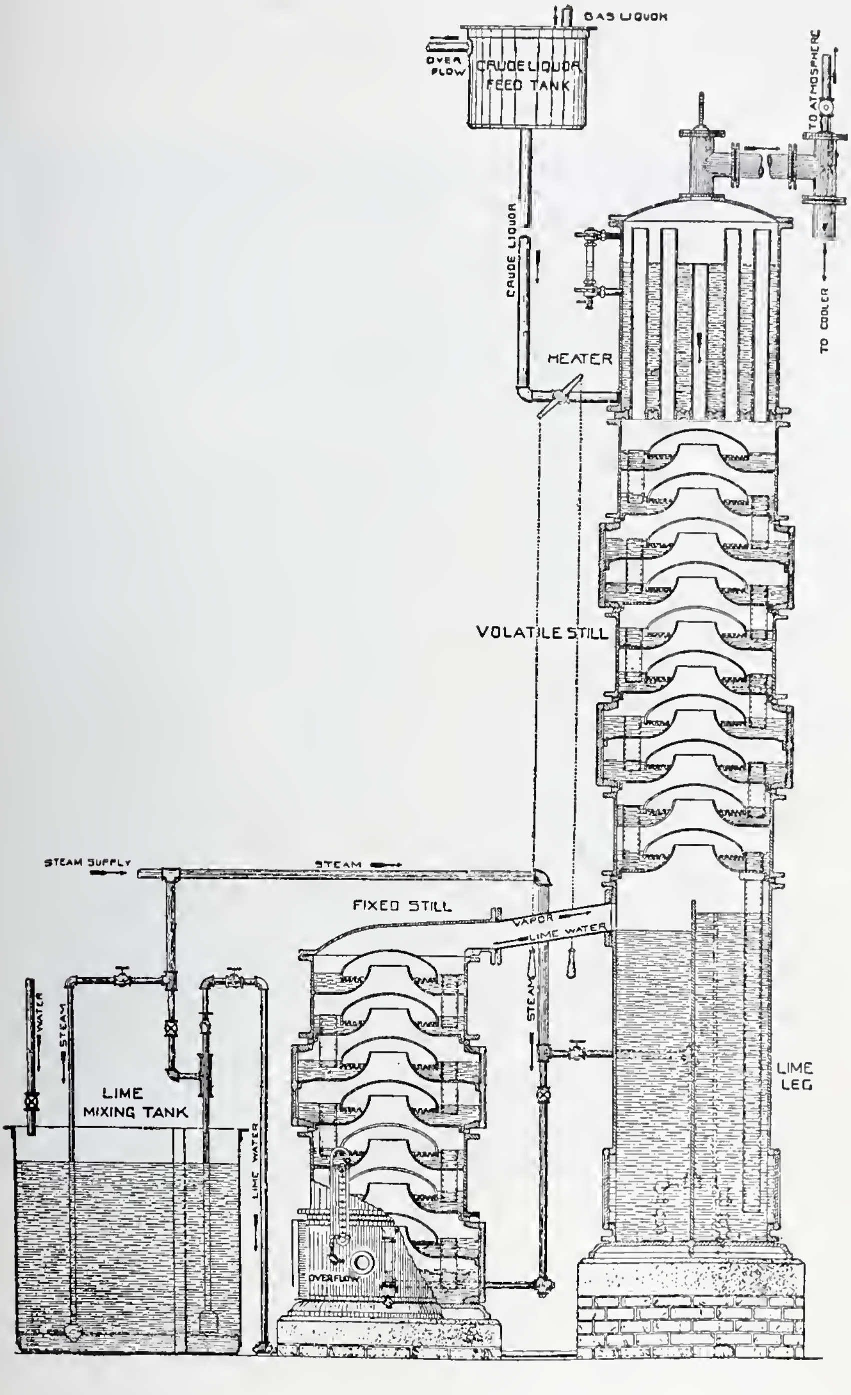

FIG. 125.—Usual Type of Ammonia Column Still.

water is available. Naphthalene separates from the gas in these coolers and is carried down in the wash water to a separating sump.

Light Oil or "Benzol" Absorbers. Following the final cooler are similar towers filled with wooden grids, the "benzol" or light oil absorbers, or washers, in which an absorbent oil, one of the heavier fractions of petroleum, or sometimes a coal-tar oil, is used as a scrubbing agent. This wash oil, at 25° C., absorbs in such scrubbers, an amount of light-oil equal to 2.0 to 3.0 per cent. of its weight. Greater saturation would be possible but is not found advantageous. The wash oil is sprayed at the top of the tower in very thorough manner so as to

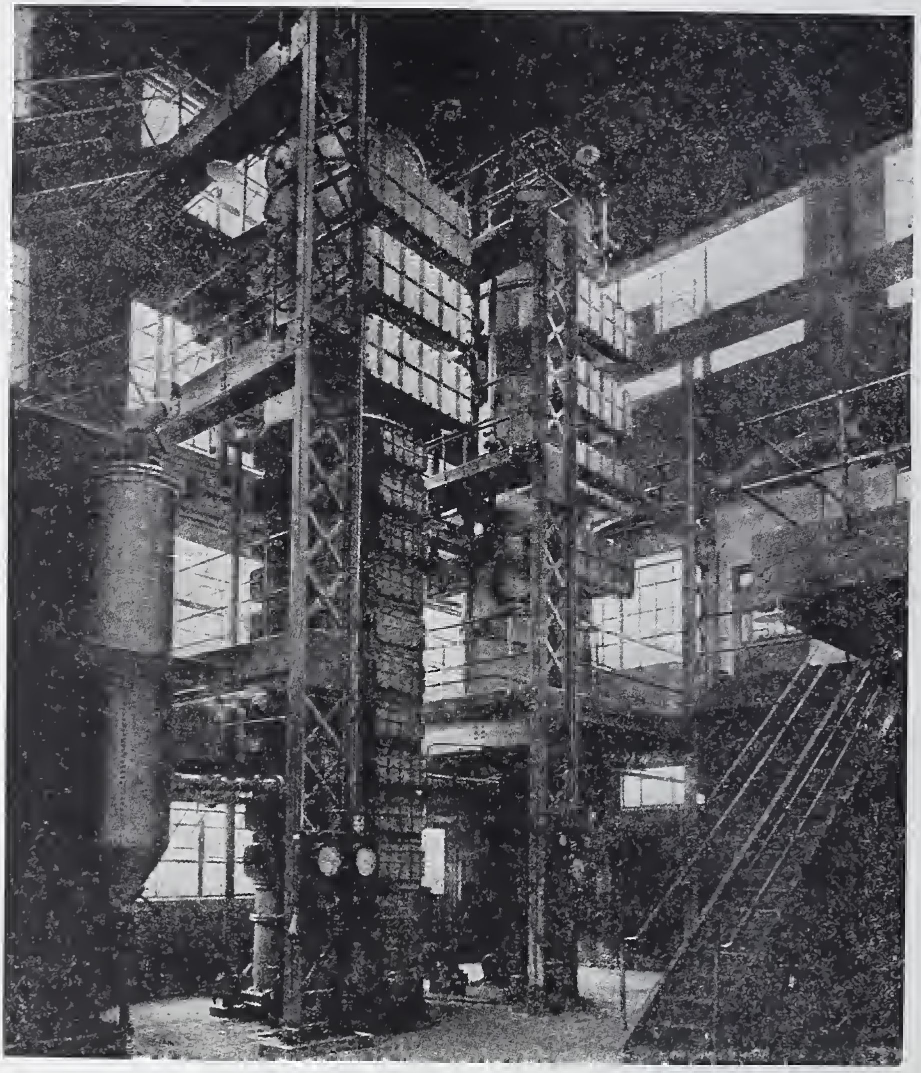

Fig. 126.—General View of Semet-Solvay Ammonia Concentrating and Purifying Apparatus.

present the maximum of surface to the ascending gas. A very important consideration in these absorbers (as in the final coolers and other applications of this type) is the ratio of scrubbing surface provided per unit of volume. Wooden grids are most commonly used as filling material and lately a form of spiral ring tile has found application. The counter flow principle is used, the gas near its outlet meeting the incoming fresh oil. In this manner there may be extracted, in a well operated plant with favorable conditions 90-95 per cent. of the total light oil vapors in the gas.

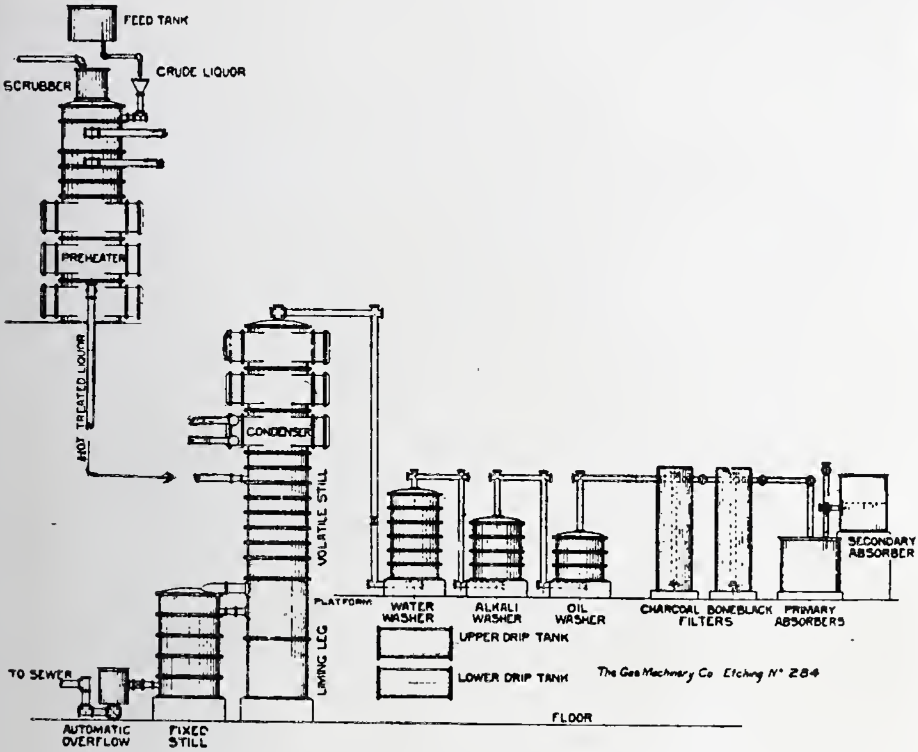

FIG. 127.—Diagram of "Aqua" Ammonia (Purified Ammonia) Plant.

The benzol washers are generally two or more in number, placed in series. They should be designed with a view to a suitable gas velocity and time of contact with the absorbent oil, the latter, for best results, being not less than 60 seconds through the series of scrubbers.[3]

A good grade of petroleum wash oil should distill 90 per cent. between 250° and 350° C., have a specific gravity of not over 0.88 at 15° C., and flow readily at 4° C. A grade commonly used is the so-called straw oil.

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[3] For explanation of the principles underlying absorption of the constituents of light oil from gas, see H. S. and M. D. Davis, "Studies on the Absorption of Light Oil from Gas," *Jour. Industrial and Eng. Chemistry,* 10, 718 (1918).

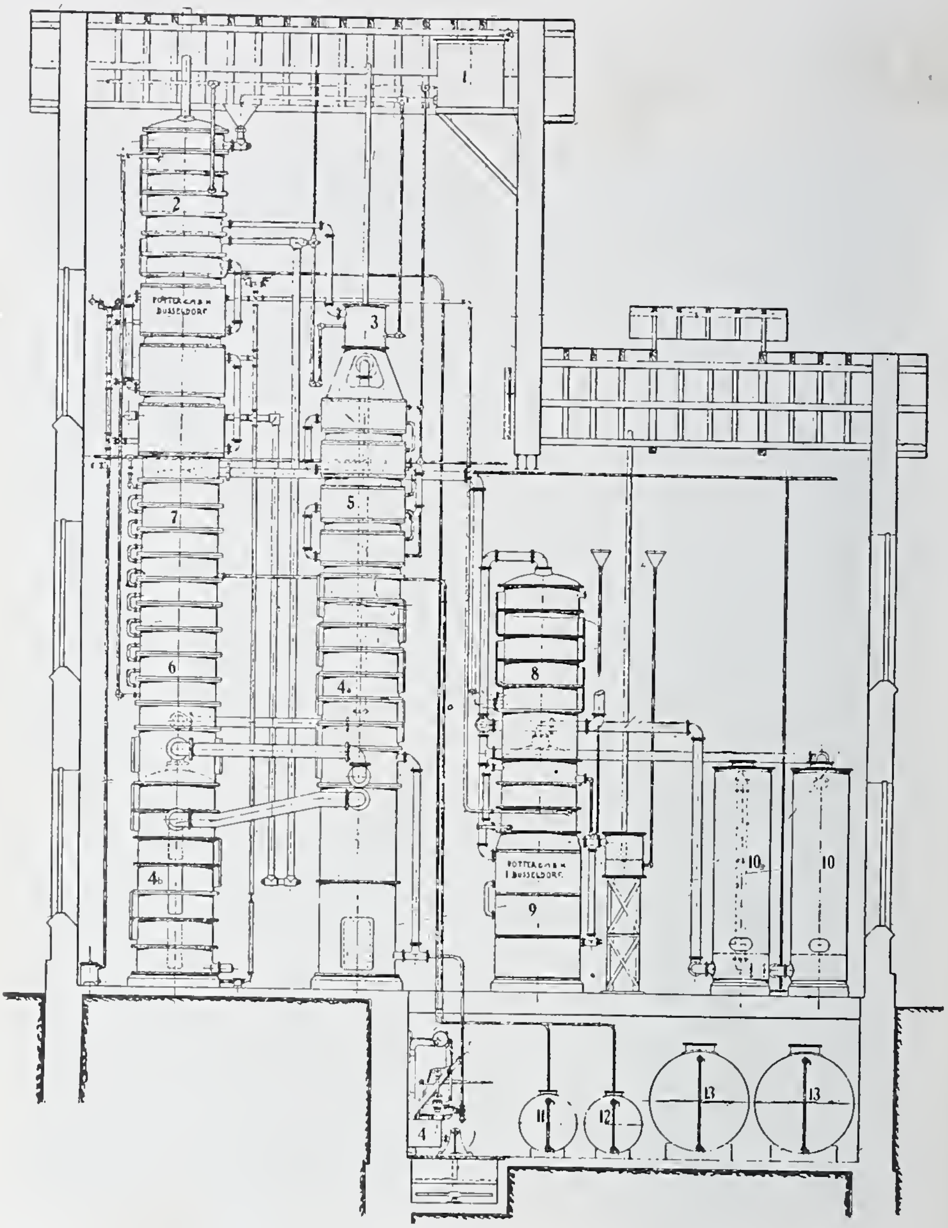

Fig. 128.—Ammonia Purification and Concentration Plant, German (after Hilgenstock, Journal f. Gasbeleuchtung, 58, 710).

Light-oil or Benzol Recovery. The apparatus used in distilling the benzolized wash oil, and for fractionating and purifying the light oil thus obtained, is elaborate, and can be described here only in outline.[4]

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[4] The reader is referred for detail on this subject to (1) "Report on the Recovery of Light Oil from Gas and the Refining of Toluol" (by the U. S.

In Figure 129 is a diagram giving the approximate arrangement of apparatus.

The enriched wash oil is pumped through heat exchangers wherein it is preheated, first by the vapors from the still, and then by the hot debenzolized oil flowing out of the still. It is further heated by steam in a super-heater and then flows into a continuous column still known as the *wash oil still*, or *stripping still.* This is made up of sections superimposed, in which the oil flows downward and the vapors upward, live steam being brought into direct contact with the oil in the lower sections.

In the Semet-Solvay stripping still there is provided an unusually large number of fractionating sections at the top of the column whereby, it is claimed, a high degree of separation is obtained of the true light oil vapors from the heavy oil. The latter, it is to be noted, is carried along with the lighter vapors, not only as liquid particles entrapped therein, but as vapor produced below the normal boiling point by the well known effect of steam distillation.

The vapors of light oil and steam pass from the still through the heat exchanger above mentioned and thence into the condenser and water-separator.

The return wash oil, debenzolized, after being cooled somewhat in the heat exchanger, is passed through coils over which flows a stream of cooling water, or through double-pipe coolers, wherein it is brought to a temperature of 25° C. (77° F.), or lower, and there recirculated through the washers.

A certain amount of wash oil, as above noted, distills with the steam and light oil from the wash oil still, and is later recovered, by fractionation of the crude light oil, and may be returned to the circulating system, after being deprived of its naphthalene content in cooling pans.

The so-called "crude stills" are tank stills of 6,000 to 15,000 gallon capacity, intermittent in operation, in which the crude light oil is fractionated by heating first with indirect steam heat from coils and then by direct steam to secure the heavier fractions. These stills are surmounted by fractionating columns, placed in Koppers practice directly over the still and in Semet-Solvay plants on separate support at one side.

For motor-fuel, one fraction from the crude still is generally made, cutting at a suitable predetermined temperature. If pure products, benzol, toluol and solvent naphtha, are desired, several fractions are made, and these redistilled with more elaborate fractionating columns.

The products from the crude still are washed with strong sulphuric acid in an "agitator" and then with caustic soda solution and finally

Bureau of Standards, collaborating with a war-time investigating commission), in *Journal of Industrial and Engineering Chemistry*, 10, 51-61 (1918). (2) W. H. Wright, Amer. Gas Institute News, 1917, November, page 608. (3) F. W. Sperr, Jr., "Notes on the Recovery of Toluol, from Gas," *Gas Age*, 41, 393-7 (1918); also in "American Fuels," by Bacon and Hamor, Vol. 1, pp. 205-212.

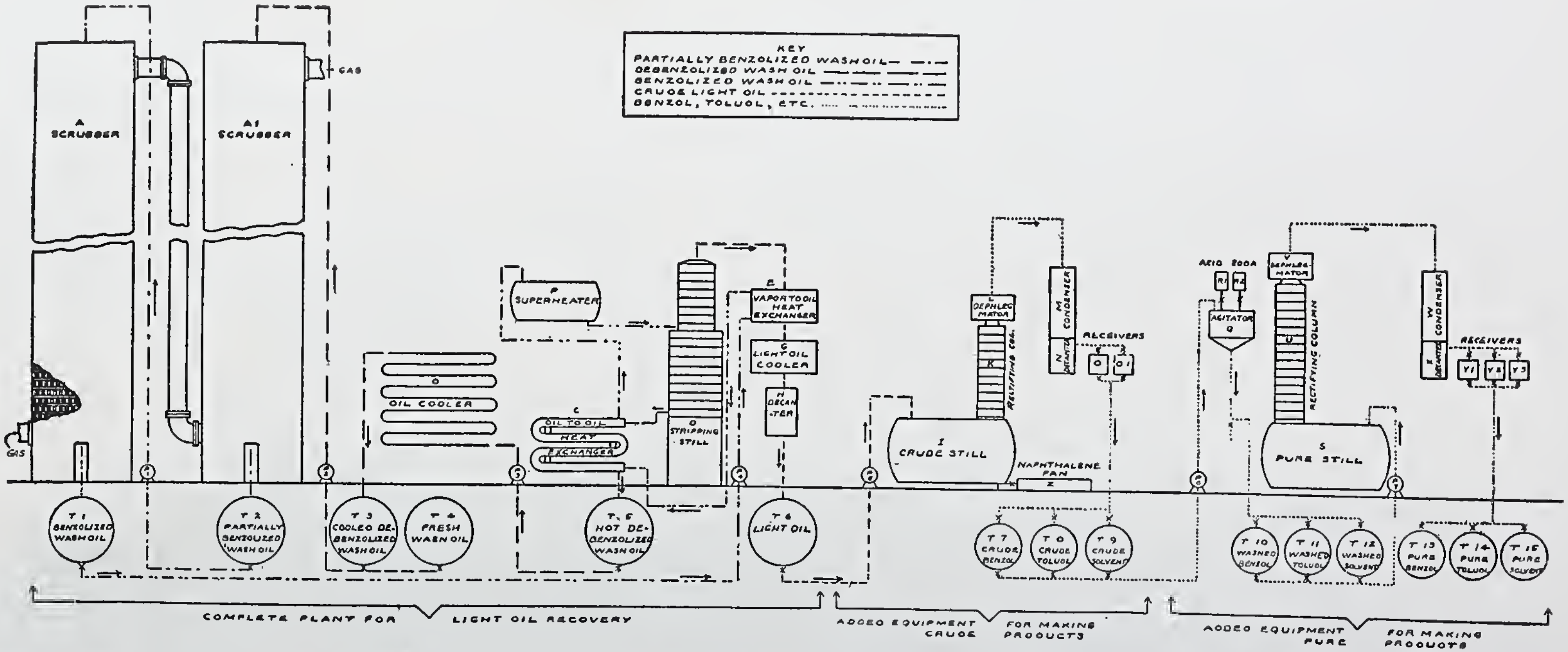

FIG. 129.—Light Oil Recovery Flow Diagram (from article by U. S. Bureau of Standards, Jour. Ind. & Eng. Chem., 10, 51).

water, to remove certain impurities, chemically of an unsaturated character, which cause discoloration and slight tarry deposits if allowed to remain in the redistilled benzol or motor fuel.

The waste acid from the agitator is generally recovered by regeneration with live steam which separates a large part of the impurities and leaves a diluted acid which may be used in ammonium sulphate recovery.

The washed products must be redistilled to be water-white and pure, since by action of the acid certain complex compounds, similar to resins, are formed from the impurities and these compounds remain in part dissolved in the benzol.

Miscellaneous Equipment. Certain important parts of the by-product recovery plant, remain to be described, but can be given only brief mention here.

The *fuel gas holder,* or (at gas works) the *"relief" holder,* receives a part of the gas as it issues from the last of the train of by-product apparatus, namely the benzol washers. At coke oven plants which burn part of this gas in their heating flues, this holder serves as a pressure-head to send the gas back to the ovens. Enough of the gas is continuously diverted to it to maintain its height at the desired constant.

The gas not required for oven heating is pumped by *gas boosters* to the destination required, often a number of miles away. These boosters are generally of the centrifugal type and driven either electrically or by steam turbine.

The practice of *gas separation,* wherein the run of gas from each coking period in an oven is separated into rich (the first part) and lean (the last part), each of which is carried separately through an entire set of by-product apparatus, has been previously mentioned in connection with the description of oven operation. This practice, not common in the more modern plants, has for its object the furnishing of rich gas of high illuminating value for public distribution, in places where a minimum candle power regulation is in effect. In plants where this practice prevails, the benzol washers are used in such manner as to scrub the lean gas completely in the usual way, and the rich gas only partially, as, for example, by the enriched wash oil from the lean gas scrubber. This serves to remove from the rich gas a part of the benzene but leaves most of the toluene, xylene, and higher homologues in the gas, with their relatively high enrichment value.

Storage tanks for tar are required, of ample capacity, and generally two or more in number. They are steel tanks of the vertical cylindrical, "cheese box" type, and provided with steam coils to assist in loading out the contents and in breaking up tar and water emulsions when necessary. Similar tanks are provided for ammonia liquor when this is made. Sulphuric acid, of 60° Baumé, or stronger, is stored in iron or steel tanks, usually of the horizontal cylindrical type.

Various Direct Ammonium Sulphate Processes Compared. The direct process in general is distinguished from the indirect by the fact of direct formation of sulphate in one step from the ammonia in the gas. A process which forms in its early stages some ammonia liquor by condensation and involves distillation of this liquor to transmit its ammonia to the saturators, is strictly speaking only in part a direct process, and in part indirect.

The Koppers and Semet-Solvay so-called direct processes, practically the only ones used in American works, are therefore semi-direct rather than direct, since both condense some aqueous ammonia liquor in the mains and primary coolers, the Koppers probably having somewhat more liquor to distill than the Solvay.

A strictly direct process is not likely to be found practicable, owing to the presence of salts of ammonia, the so-called "fixed ammonia" in important quantities in the raw gases from the ovens. The vapor of ammonium chloride, causes corrosion of the pipes and apparatus and if carried into the saturator would there form hydrochloric acid, whose vapors are extremely corrosive. It is best therefore to keep this salt dissolved in the liquor of the collecting main and coolers.[5]

The Otto direct process, applied in some European plants, uses a "dry" main flushed only with tar, dispenses with water-cooled condensers and maintains the temperature of the gas above the dew-point of the aqueous liquor it carries. Tar fog is extracted by drawing the gas at 100° C. (212° F.), through a throat by a nozzle spray of hot tar. In later installations liquor is used in this spray in order to dissolve ammonium chloride from the gas. The free ammonia and most of the water vapor are carried on into the saturator.

The Simon-Carves direct process, also used in Europe, is like the Otto in attempting to dispense entirely with liquor condensation, by keeping the temperature of the gas above the dew point. It makes

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[5] C. C. Tutwiler, in a paper before The Franklin Institute, Oct., 1914 (*J. Frankl. Inst.*, 1914, 383-415), presents an analysis of ammonia liquor sampled from the hydraulic (collecting) main of a gas works, comparing same with an analysis of an average sample of the total liquor (from the well) as follows:

TABLE 36.

ANALYSES OF AMMONIA LIQUOR.

(Figures represent grains per U. S. gallon.)

	Well	Hydraulic Main
Total NH_3 found by direct distillation	1,446.0	362.0
“ “ as calculated from the sum of component salts	1,440.3	316.0
NH_3 as mono carbonate	1,283.0	36.7
“ “ “ sulphide	81.7	6.5
“ “ “ thio-sulphate	8.7	46.6
“ “ “ sulphate	4.5	6.4
“ “ “ chloride	32.1	192.4
“ “ “ sulpho-cyanide	26.8	26.2
“ “ “ ferro-cyanide	3.5	1.2
“ “ “ cyanide	....	....

use of centrifugal machines and a cyclone extractor to remove the tar. This process also has been compelled to adopt the use of liquor to wash the ammonium chloride from the gas.

The Semet-Solvay direct process (so-called) flushes the mains with the liquor of condensation (derived largely from the water of the coal and of its decomposition), and circulates also weak liquor in the primary washer cooler, giving the circulating liquor only a limited amount of cooling in outside cooling coils. A large proportion of the tar is extracted in the washer-cooler and practically all of the fixed ammonia. After passing the centrifugal exhauster, which extracts some tar, the gas is then treated in an "economizer," with the liquor of condensation, this time preheated by outside steam coils so that the free ammonia and some moisture is taken up from the liquor, and the gas becomes heated. In effect the liquor serves to wash out both tar and the fixed ammonia salts, and is concentrated in the economizer by the heat and the passage of the gas.

Conservation of the sensible heat of the oven gases and of the latent heat of their vapors by direct cooling with ammonia liquor so as to accomplish the desired concentrating of the latter, and evaporate its free ammonia, as is provided in a measure by the Semet-Solvay process, constitutes the logical development of by-product recovery in accordance with sound principles of economy. The use of cooling water for the primary cooling of the gas, running to waste the heat absorbed thereby, and in the same system expending steam to distill free ammonia from the condensed liquors, and to return heat to the gas, constitute a method, wrong in principle and wasteful of the heat originally imparted to the oven for effecting carbonization. In this connection a recent patent of F. F. Marquard (U. S. Pat. 1,455,299, May 15, 1923), for evaporating ammonia liquor in a baffle tower by an upward current of hot gas, is worthy of especial note.

The Koppers direct process (so-called) flushes the mains with tar and liquor thus retaining in the latter most of the fixed ammonia. It cools the gas to 30° C. (86° F.), thereby condensing much of the liquor content, and carrying down therein about 25 per cent. of the total ammonia from the coal. This liquor must all be distilled to send its ammonia content into the saturator. The gas after being cleaned in the P. & A. tar extractor, is reheated, as has been described, in order to produce favorable conditions of concentration and temperature in the saturators. It is claimed that this process particularly gives a well-cleaned gas and at the same time the necessary control of temperature and humidity at the entrance to the saturator.

Tar Distillation Plant. In the class of secondary by-products of coal carbonization, which comprises also the purified products of light oil and of ammonia liquor, are to be placed the distilled fractions of tar and their many highly developed derivatives. The description of the tar distillation plant, which only rarely is a constituent part of the coke oven plant or gas works, can be given here only in outline.

Figure 130 gives a general outside view of a tar distillation plant. In Table 46, pages 327-9, is given a partial list of the fractions and principal derivatives of tar distillation.

The description refers to the tar obtained in high temperature carbonization of coal; low temperature tar is different in quality and composition and receives different refining treatment (see page 322).

Dehydrators, or preheaters, in which the tar is heated usually to 170° C. (338° F.), to remove water and free ammonia and light oil, are often designed so as to heat the tar in a thin film to avoid frothing. A type of tar dehydrating apparatus, demonstrated by practical use, is described by A. W. Warner in Amer. Gas Assoc. Monthly, 4 (1922), pp. 437-8. The ammonia water thereby obtained is sent to the ammonia plant stills and the light oil to the crude stills of the benzol plant.

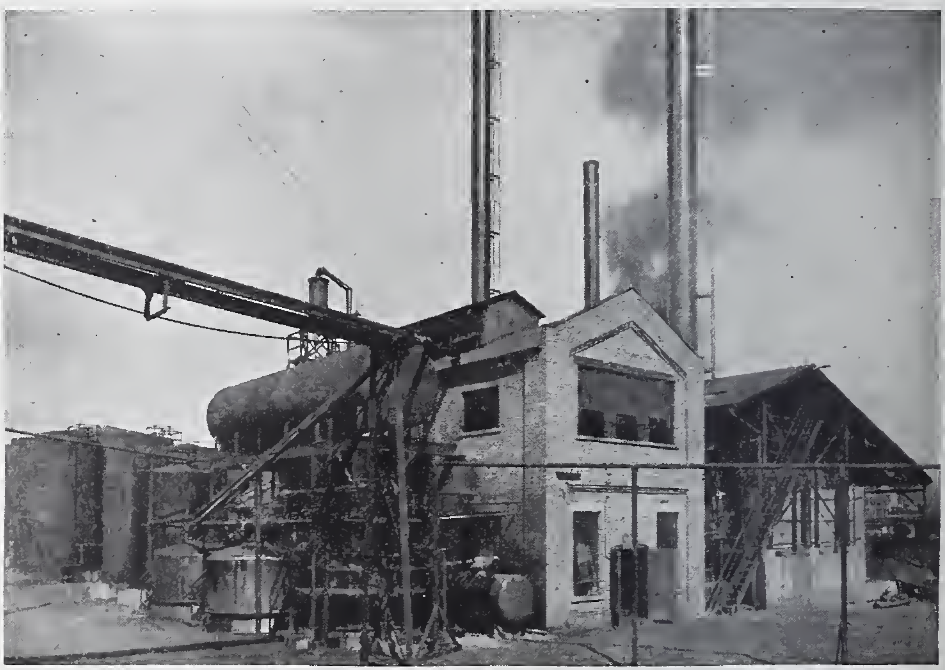

Fig. 130.—Tar Distillation Plant, Usual Intermittent Type (bricked-in stills to be seen on right).

The crude *tar still* receives the hot tar from the dehydrators and carries the temperature gradually higher by means of direct firing. The still is ordinarily of the horizontal cylindrical boiler type, bricked in (over half its height) and fired by coal or gas. It may be provided advantageously with an arrangement of flues whereby the heat of the waste gases preheats the tar, or with heat exchangers, used in English practice, whereby the latent and sensible heat of the vapors is recovered.

A worm condenser is commonly used, now frequently of wrought iron, welded. The receiver is changed after each fraction.

The first fraction, water and light oil, to 170° C. (338° F.), is often obtained direct from the still, but in later practice frequently also in a separate apparatus, the dehydrator. Fixed ammonia salts, in this early fraction, are very corrosive to the still tops, especially if these are of wrought iron or steel instead of cast iron.

The carbolic acid fraction, with naphthalene, distilled at 170°-235° C. (338°-455° F.), is cooled in crystallizing pans, the naphthalene centrifuged out, and the oil treated with caustic solution for recovery of "tar acids" whereby crude phenol (carbolic acid) and cresols are obtained.

The next higher fraction at 235°-270° C. (455°-518° F.), is also cooled for naphthalene recovery, the oil residue being then mixed with the oil remaining from the tar acid recovery in the preceding fraction, and disposed of as *creosote oil.* This valuable product may be varied in composition and gravity as required by specifications and the state of the markets, leaving therein more or less of the tar-acids, naphthalene, etc.

The fractionation above 270° C. (518° F.), depends on the requirements of the market for the products. Soft pitch is in greater demand in America than hard pitch and anthracene. The fractions above 270° C., viz. 270°-315° C. (518°-599° F.), and 315°-355° C. (599°-671° F.), contain anthracene (with phenanthrene and carbazol), and anthracene oil, and leave a residue of hard pitch. On the other hand if the distillation is stopped at 270° C. (518° F.) or slightly higher, the residue is soft pitch for which a good commercial demand exists for a variety of uses. Pitch may be softened materially by mixing in a part of the crude naphthalene obtained from the middle fractions.

The amount of free carbon in the tar affects greatly the quality of the pitch, and commonly the raw material is so chosen, on the basis of analysis, that the resulting pitch will meet the requirements of the particular market at hand.

Continuous Tar Distillation. The intermittent process outlined in the preceding paragraphs, is the system used generally (at the time of this writing), throughout the American tar industry. Continuous tar distillation, on the other hand, is, in European countries, coming into use, having passed the experimental stage. In England, and on the continent of Europe, several plants are in commercial operation. In principle this process is economical of fuel and of labor.

The Hird process,[6] developed in England, was installed in 1920 at the works of the Coopers Creek Chemical Co., West Conshohocken, Pa. (near Philadelphia), and has been operating successfully there since that time, largely on coke oven tar. The tar, after being preheated, flows continuously and in series through four stills (A to A_4, Figure

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[6] An English installation using this process is described in *Gas World*, 71, 17-21 (Coking Section) (1919).

131) at a rate of about 250 gallons per hour. As each still holds 250 gallons, it follows that the tar remains about one hour in each still, subjected to the heating conditions therein.

The different stills are operated at temperatures about as follows:

A_1	177°–205° C.		350°–400° F.
A_2	232° C.		450° F.
A_3	274° C.		525° F.
A_4	232° C.	(Direct steam admitted)	450° F.

The first three stills are heated continuously by the hot gases from coke breeze furnace or fuel gas burners passing through horizontal

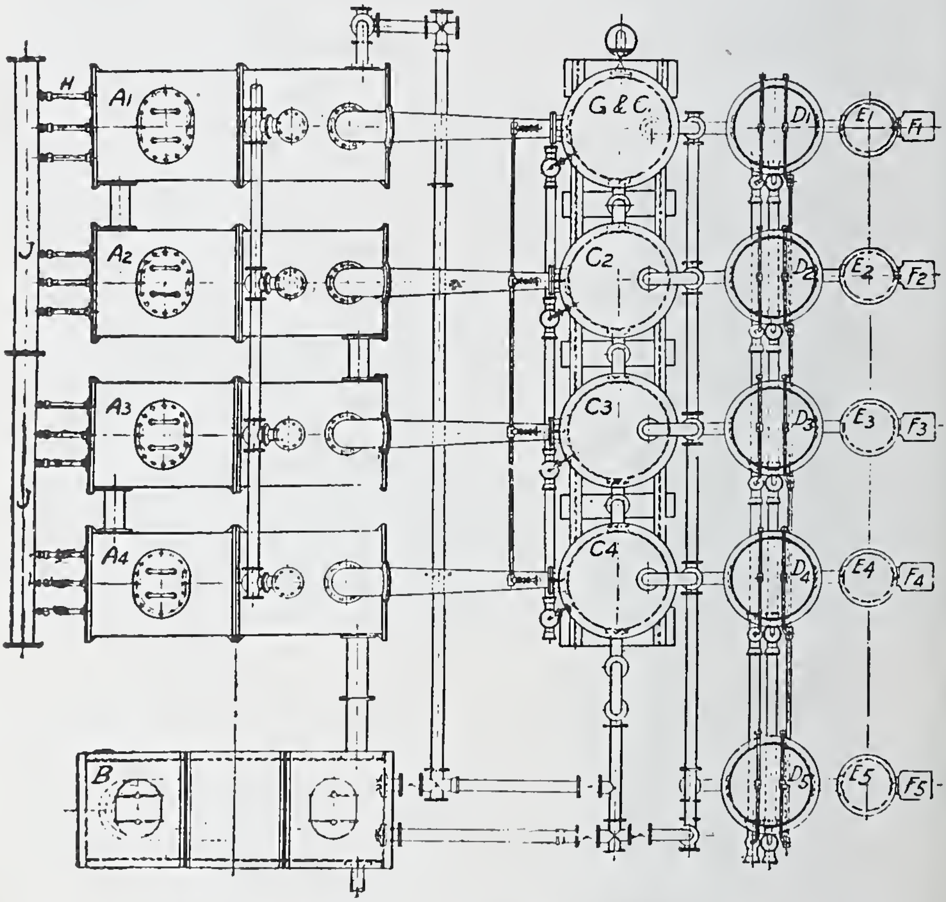

Fig. 131.—Hird's Continuous Tar Distillation Plant; Plan Drawing.

tubes in the bottom part of each still. Provision is made to heat A_4 in the same manner, but direct heating, in this manner, is applied here only when starting the plant, or when excess capacity is desired. Baffles are arranged in each still so as to increase the length of flow of the tar. There is a depth of tar of about 15 inches in each still.

From still A_4 the tar residue, or molten pitch, flows into the pitch cooler B, which is virtually a heat exchanger, delivering part of the heat of the pitch to the incoming tar. The latter passes through coils in B on its way to still A_1, and is preheated thereto to 93°-121° C. (200°-250° F.), the pitch being cooled sufficiently to be loaded out into barrels without objectionable fuming.

From still A_1 light oil is obtained, from A_2 and A_3 creosote oil, and from A_4, by steam distillation, anthracene oil. If desired, A_4 may be operated at higher temperatures to produce hard pitch.

The preheaters C_1, C_2, C_3 and C_4, receive in succession the incoming raw tar which passes in each around a coil carrying the hot vapors from the stills. In these preheaters the tar is discharged of its content of water and ammonia and the lower-boiling light oils, which are recovered in a separate condenser. From preheater C_4 the tar passes through the coils in the pitch cooler, B, and thence to the stills.

The system of heat exchange and the method employed for pitch cooling in this process make for fuel economy, convenience in operating control, and a minimum of priming troubles.

The plant is constructed of cast iron, except for the tubes in the stills, which are of steel and require renewal at intervals of one to two years. Corrosion in other parts, as in stills and preheaters by ammonium chloride and cyanides driven over with the light vapors, is reduced to very small proportions by the use of cast iron.

American Experience in Continuous Tar Distillation. Actual operating records of the above-named American plant examined by the author, show that this plant has been run for long periods on a monthly consumption of 130,000 gallons of low-carbon coke-oven tar, with an average of 5,000 gallons per day, or 25 per cent. in excess of its rated capacity. Using for a short time, coke oven gas for fuel, it required 6-6½ cubic feet per gallon of tar distilled. Coke breeze was substituted and has proven more economical, the requirement having averaged over a long period, 0.7 pound per gallon of tar (larger on a heat unit basis than that of gas, but cheaper in actual cost owing to relative prices).

The economy of fuel and labor in a plant of this size, as compared to the modern intermittent still equipped with preheater and separate pitch cooler, is not found to be large, but, on a plant of 100 tons (20,000 gallons) daily capacity, it is believed, would be important.

The continuous process, in the experience of the American users, thus far gained, has shown marked advantages in its simplicity of operation and low maintenance cost, its economy of space and suitability to enclosure by housing, its cast iron construction insuring long life, and in the element of safety from fire, secured by the fact of its relatively small amount of tar in run distributed in a number of compartments.

There has been found to be, also, an advantage in flexibility and there is opportunity for ready control of quality in the output, but the

American experience has indicated, as above noted, little advantage in costs, except in those of depreciation and maintenance.

Koppers Process for Continuous Tar Distillation. The Koppers Company has proposed[7] a process for continuous tar distillation in which the tar flows through a number of vertical cylindrical stills, rising in an annular space and descending through a central vertical tube.

This process is not yet in a position to furnish data of actual working on a commercial scale.

Raschig Process of Continuous Tar Distillation. The Raschig Process is said to have attained marked success in a number of plants operated commercially on the continent of Europe. It is described by H. A. Prager in *Gas World,* Sept. 1, 1923, Volume 79, Coking Section, page 20.

Miscellaneous New Processes in By-Product Recovery.

Electrical Precipitation of Tar from a suspension of its fine particles in gas, through the agency of a high-potential current (conforming to F. G. Cottrell's basic patents on electrical precipitation), has been given much study and careful experimentation. A patent was granted Feb. 6, 1923 (U. S. Pat. No. 1,444,627), to A. F. Meston, for a combination of scrubber, and electrical tar precipitator especially adapted to the cleaning of coke oven gas (U. S. Pat. No. 1,393,712 also was granted to F. W. Steere and W. C. Woodland, Oct. 11, 1921, for a process of electrical precipitation of tar from gas).

Direct Process for Ammonium Sulphate using Zinc Sulphate. There has been proposed and patented,[8] by Prof. J. W. Cobb of the University of Leeds, England, an ammonia recovery process whereby part of the sulphur in the gas is utilized. A solution of zinc sulphate washes the gas, thereby precipitates ZnS by reaction with the hydrogen sulphide in the gas, and forms ammonium sulphate with the ammonia in the gas. The zinc sulphide is collected, and roasted to form oxide and SO_2, which latter then is used to regenerate sulphate with the zinc oxide. The zinc accordingly is not lost, and serves only as a carrier of the sulphur from the gas to the ammonium sulphate.

There appears to be some uncertainty whether in this process the added cost of evaporating the ammonium sulphate solution will be counterbalanced by the saving of sulphuric acid, and whether the sulphate of ammonia can be kept free of contamination with sulphate or sulphide of zinc, by a proper balance at all times between H_2S and NH_3 in the gas.

The Bregeat Process for Benzol Recovery. This is an absorption process, which has been used with considerable success in France,[9] and lately introduced into America. It uses a mixture of cresols, of specific gravity 1.044 and boiling range 185° to 203° C. (365°-397° F.), as the absorbing medium. The advantage claimed over the more usual absorbents is greater absorbing power for benzol vapors (such absorbing power being, it is claimed, 6 per cent. to 10 per cent.), and, as consequent thereto, the possibility of a cheaper and simpler absorbing and distilling plant. The cresol acts in some measure as a solvent for naphthalene and other accumulations in the system, tending to obviate the interruptions that may occur thus with use of other absorbents. The benzols are said to form with the absorbent a molecular attachment, easily broken apart by heat, rather than a mere solution, as with the more common petroleum oil absorbents.

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[7] Trade Circular, 1921.

[8] Brit. Pat. No. 13141 (June 4, 1912) abstracted in *London Gas Journal,* Sept. 30, 1913, p. 939.

[9] For description of French installation, see A. Grebel, *Le Genie Civil,* Nov. 8, 1919 (abstracted in *London Gas Journal,* **149**, 364-5 and 432-3 (1920)).

The Bregeat Corporation of America completed, about January 1, 1924, the first American installation of the Bregeat benzol recovery process, at the by-product coke plant of the Bethlehem Steel Co., Northampton works, Bethlehem, Pa. This plant is scrubbing [10] 8,000,000 to 10,000,000 cubic feet of coke oven gas per day, through one scrubbing tower, 75 feet high and 16 feet in diameter, packed with the usual wooden grids. The flow of absorbent is said to be approximately twenty times the light oil production, or less than ½ of that commonly used with petroleum oil absorbents.

The absorbent is a mixture of "tar acids," 95-99 per cent. cresylic acids, in which it is claimed the light oil vapors are absorbed to the extent of 8 per cent or higher. Coke oven gases carrying 30 grams light oil per cubic meter result, it is claimed, in a vaporization loss of the absorbent not amounting to more than .8 gram per cubic meter at 50° C. (122° F.), that is, about .15 per cent. of the absorbent oil in circulation. The saving in steam and power for circulation and stripping, it appears, should compensate for the loss of cresol by vaporization.

Plant operation has not, as this is written, been continued long enough in this country to permit a true judgment of relative costs, losses, and recoveries.

Charcoal as a Benzol Absorbent. This material (especially prepared as an absorbent by methods developed in wartime for gas-mask application) has found successful practical application as an absorbent on the large scale for the gasoline vapors in natural gas, and on an experimental plant scale for benzol recovery from coal gas. The material when saturated can be discharged of its absorbed vapors, in situ, by a current of steam, and the carbon activated or revivified by further heating in superheated steam. The absorbent is said not to remove ethylene and similar hydrocarbons permanently from the gas since continued absorption of the higher boiling constituents, benzol, etc., displaces any ethylene at first absorbed. Advantages claimed on the basis of an experimental plant trial in France[11] are (1) high absorbing power (for benzols 25 per cent.) making possible a smaller installation and lower cost (estimated at two-thirds of oil washing plant), (2) simplicity of operation requiring no transfer of liquid absorbent for distillation and a lesser amount of purification of recovered light oil, and (3) lower replacement cost of absorbent as compared to wash oils.

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[10] The data here given on this installation have been furnished by the Bregeat Corporation of America, 50 East 41st St., New York, in private communication to the author.

"Silica-Gel" as an Absorbent. This material is a massive, but light, form of hydrated silica permeated with microscopic pores equal in aggregate volume to 45 per cent. of the total. It has been found applicable and efficient for "selective absorption" of vapors of many kinds industrially. When activated it has, like active charcoal, a very high absorptive power, and has been applied experimentally on a small scale to the absorption of benzols from gas. Certain drawbacks, such as for example the preferential absorption of water with consequent lowering of activity toward the benzols, appear to be hindering advance in the use of this material industrially for benzol recovery.

Gas Purification by the "Liquid" Process. The subject of gas purification, meaning the extraction of sulphur and cyanogen compounds, is highly important in the manufacture of gas for public distribution. It has been most commonly carried out by passage of the gas through beds or "boxes" of solid purifying material, usually hydrated iron oxide mixed with wood shavings.

Mention is properly to be made, here, of the new *"Seaboard" Process of Liquid Purification of Gas,* (U. S. Pats. 1,389,980, Sept. 6, 1921, and 1,436,196, Nov. 21, 1922) (see complete description of this process by F. W. Sperr, Jr., in Amer. Gas Association, Technical Section Sessions, Vol. 3 (1921), pp. 282-363).

This process uses a solution of sodium carbonate to wash the gas, in a wash tower or absorber similar to the benzol washers already described, filled either with wooden hurdles, coke, or spiral ring tile to provide a large scrubbing surface. In another similar tower, somewhat larger, the fouled solution is "actified" by air blown through the liquid at a rapid rate from the bottom and is then returned for re-use in the absorber. It is found most economical to combine the treatment in these liquid scrubbers with a final "wash" in "catch boxes" containing iron oxide. It is possible, however, by resorting to a stronger solution, more rapid circulation, the use of two scrubbers in series, and a "secondary actifier" to discharge the solution completely of sulphur compounds to remove *all* of the hydrogen sulphide by the liquid process. The solution is advantageously of a strength of 30 grams per liter (¼ pound per gallon) and is circulated at a rate of 50 to 60 gallons per 1,000 cubic feet of gas, but these figures are varied to suit conditions. If the solution is thoroughly activated and the size of apparatus is such as to secure proper flow ratios the reduction of the hydrogen sulphide in the gas may readily be made between 80 and 90

[11] A. Engelhardt, *London Gas Journal,* 159, 421 (1922) (Abstract).

per cent., or, from 400 grains per 100 cubic feet to 60 grains per 100 cubic feet, this residue being then easily removed at low cost in the iron oxide catch boxes. Hydrocyanic acid is entirely removed in the liquid scrubber. The process does not remove carbon bisulphide or other organic sulphur compounds from the gas. Owing to the small amount of hydrogen sulphide remaining in the gas which enters the oxide purifiers, the iron oxide can be continuously revivified by the introduction with the gas of a small amount of air, so small in this case that the nitrogen added thus does not seriously lower the heating value of the gas.

Detailed data as to theoretical reactions, operating methods and results, by this process, and the operating costs in a large plant,[12] are to be found in the article by Sperr above referred to (Amer. Gas. Assoc., Techn. Sect. Sessions, 3, 282) and in later articles; F. W. Sperr, Jr., on "Progress in Liquid Purification," Proceedings Amer. Gas Association, 1923, pp. 1200-1232, and E. H. Bird, *Chemical & Metallurgical Engineering,* 29, 16-18 (1923)).

The advantages claimed, as compared to dry processes of purification, are (1) reduced costs, (2) complete removal of cyanogen compounds and (3) greater reliability, efficiency and elasticity.

The By-Products, Description of, and Theory of their Formation.

Coal Gas.

Description and Composition. The gas obtained from coal carbonization varies in composition according to the method used in its manufacture. The gas is formed by decomposition of the organic substance of the coal, and, more largely, by secondary decomposition of the tars, oils, vapors and primary gases by heat. The conditions established by the shape and size of apparatus and method of operating, therefore influence preponderantly the yield and quality of the gas finally recovered.

In general, the cleaned and purified coal gas commonly obtained in industry consists mainly of methane and hydrogen (aggregating 83-86 per cent.), with smaller quantities (3-6 per cent.) of the richer hydrocarbons—having higher carbon-hydrogen ratio than methane, of carbon monoxide (5-7 per cent.), and of "inerts"—carbon dioxide and nitrogen (5-6 per cent.). The gas from low temperature carbonization is made up of a larger proportion of the richer hydrocarbons and less of hydrogen. It is a rich gas, often of a heating value 50-75 per cent. greater than that of the usual oven, or retort, gas.

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[12] The actual cost at the plant of the Seaboard By-Product Coke Co. over a period of two weeks, purifying 25,000,000 cubic feet of gas per day of 281 grains H_2S per 100 cubic feet, by the Liquid Process supplemented by catch boxes, is given as 0.472 cents per thousand, not including royalty and capital charges.

In Table 37 are given typical, average compositions of coke oven gas, horizontal retort gas, and vertical retort gas, and an approximate average analysis of the gas from low temperature carbonization, as obtained industrially.[13] There are appended also the gross heating values per cubic foot and the average yield—in heat units (B.t.u.) per pound—from the kind of coal used at the average carbonizing plant.

TABLE 37.

Composition of Various Kinds of Coal Gas (Averages, Purified from H_2S).

	Coke Oven Gas * (Run-of-oven)	Vertical Retort Gas (Without Steaming)	Horizontal Retort Gas	Low Temperature Carbonization Gas †
Carbon dioxide	1.8	2.0	1.5	5.0
Carbon monoxide	6.3	5.5	6.0	6.5
Oxygen	0.2	0.2	0.2	0.5
Illuminating hydrocarbons	3.7	3.6	5.6	8.0
Methane	31.6	33.1	31.0	46.0
Ethane	....	1.8	....	12.0 ‡
Hydrogen	53.0	51.0	52.5	17.0
Nitrogen	3.4	2.8	3.2	5.0
	100.0	100.0	100.0	100.0
B.t.u. per cubic foot, at 60° F. and 760 mm.	586	615	615	950
Average yield of B.t.u.'s in gas per pound of coal	3,715	3,250	3,325	1,750

* Not debenzolized; using high grade coal mixture containing 10 per cent. low-volatile coal.

† Based on results of 100-pound tests in horizontal retorts at 600° C.

‡ Includes other higher hydrocarbons of homologous composition.

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[13] This is necessarily an approximation, since those plants in operation in Europe have not published analyses to be depended upon as representative of continuous commercial operation, and the one American plant which has operated commercially has not been under typical low-temperature conditions. The results of the British Fuel Research Board (Report for 1920-21, 2nd section, pp. 47-55) are most useful in this connection.

The composition of gas obtained from Koppers coke ovens is shown in Table 38.[14]

TABLE 38.

TYPICAL ANALYSES OF GAS FROM KOPPERS BY-PRODUCT COKE OVENS.

	CO_2	Illuminants	O_2	CO	H_2	CH_4	N_2	B.t.u.	Specific Gravity
Straight gas before removing benzols	2.2	3.5	0.3	6.8	47.3	33.9	6.0	591	0.44
Straight gas after removing benzols	2.2	2.6	0.3	6.9	47.8	34.2	6.0	562	0.42
Rich gas before removing benzols	2.6	4.3	0.2	6.3	46.3	35.0	5.3	630	0.45
Rich gas after removing benzols	2.6	3.2	0.2	6.4	46.8	35.4	5.4	605	0.42
Lean gas before removing benzols	2.1	2.0	0.3	6.0	57.0	27.0	5.6	528	0.38
Lean gas after removing benzols	2.1	1.0	0.3	6.1	57.5	27.3	5.7	497	0.35

These analyses are taken from different plants, and consequently represent different coals and somewhat different operating conditions.

The average debenzolized oven gas made in the Koppers ovens of the Carnegie Steel Co., Clairton, Pa., is reported by F. F. Marquard[15] in 1919, as follows:

TABLE 39.

AVERAGE COMPOSITION, BY-PRODUCT COKE OVEN GAS; DEBENZOLIZED. AS OBTAINED FROM 100 PER CENT. "KLONDYKE" (WESTERN PENNA.) COAL, IN 18¼-INCH OVENS ON 19-HOUR COKING TIME.

CO_2	2.0	per cent.
Illuminants	3.2	
Oxygen	0.3	
CO	5.5	
CH_4	32.3	
Hydrogen	51.9	
Nitrogen	4.8	
	100.0	
Specific gravity	0.394	
B.t.u. per cubic foot	569.0	
H_2S, pounds per 1,000 cubic feet	0.61	
Naphthalene, gr. per 100 cubic feet	0.95	

A number of analyses of gas from Semet-Solvay ovens are given in Table 40.[16]

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[14] "American Fuels," by Bacon and Hamor, 1922, Chapter 3, by F. W. Sperr, Jr., p. 189.

[15] Year Book, Amer. Iron and Steel Institute, 1919.

[16] Furnished by Milwaukee Coke & Gas Co.

TABLE 40.

SEMET-SOLVAY OVENS (RECUPERATIVE).

The Milwaukee Coke & Gas Company.

ANALYSES OF RICH AND LEAN GAS.

RICH GAS.

	CO_2	C_6H_6	C_2H_4	O_2	CO	CH_4	H_2	N_2	$\frac{CH_4}{H_2}$	Coking Time	Coal Mixture Per Cent. High Volatile	Coal Mixture Per Cent. Low Volatile
Nov. 1919......	2.3	1.2	3.2	.4	6.0	34.3	46.7	5.9	.73	13.71	74.0	26.0
Dec. 1919......	2.3	1.0	2.9	.2	5.6	34.4	47.4	6.2	.72	13.68	68.7	31.3
Jan. 1920......	2.2	1.1	2.9	.3	4.9	34.9	47.4	6.3	.71	13.70	69.8	30.2
Feb. 1920......	2.2	1.2	2.8	.3	4.3	35.0	47.6	6.6	.74	13.71	69.9	30.1
Mar. 1920......	2.2	1.2	3.0	.3	4.9	34.5	47.4	6.5	.73	13.78	75.6	24.4
Apr. 1920......	2.8	1.6	3.3	.3	5.1	34.0	44.2	8.7	.77	22.88	74.2	25.8
May 1920......	2.8	1.5	3.1	.3	5.0	34.8	44.6	7.9	.78	21.18	77.8	22.2
June 1920......	2.8	1.3	2.7	.2	5.0	35.1	45.0	7.9	.78	19.18	70.2	29.8
July 1920......	2.3	1.1	2.4	.3	4.4	35.0	46.7	7.8	.75	19.19	76.7	23.3
Aug. 1920......	2.0	1.2	2.3	.3	4.5	35.8	47.1	6.8	.76	19.20	65.6	34.4
Sept. 1920......	2.1	.9	2.3	.3	4.3	36.4	47.9	5.8	.76	18.52	69.5	30.5
Oct. 1920......	1.8	.8	2.7	.3	5.0	35.2	45.8	8.4	.79	16.51	69.6	30.4
Ave.	2.3	1.2	2.8	.3	4.9	35.0	46.5	7.0	.75	17.10	71.8	28.2

				Lean Gas.						Gas Yield (Thousands)		
										Rich	Lean	Total
Nov. 1919......	1.7	.3	2.1	.3	6.2	27.0	55.4	7.0	.56	2.87	6.88	9.75
Dec. 1919......	1.6	.3	1.9	.3	5.9	26.7	55.7	7.6	.48	2.68	7.05	9.73
Jan. 1920......	1.6	.2	1.7	.2	5.5	27.4	56.5	6.8	.48	2.72	7.01	9.73
Feb. 1920......	1.6	.3	1.9	.4	5.1	27.1	55.0	8.6	.49	2.78	7.00	9.78
Mar. 1920......	1.8	.4	2.1	.3	4.9	27.4	55.3	7.8	.49	2.57	6.96	9.53
Apr. 1920......	1.9	.4	1.4	.3	6.0	23.7	52.7	13.6	.45	3.17	7.42	10.59
May 1920......	2.2	.4	2.0	.3	5.0	27.1	51.9	11.1	.52	3.48	6.77	10.25
June 1920......	2.1	.4	1.8	.3	5.3	25.4	56.1	8.6	.45	3.70	6.41	10.11
July 1920......	1.9	.5	1.9	.3	4.5	27.2	55.0	8.7	.49	3.97	6.44	10.41
Aug. 1920......	1.4	.3	1.6	.4	4.9	26.5	56.6	8.3	.47	3.85	6.44	10.29
Sept. 1920......	1.6	.3	1.9	.3	4.2	26.5	55.4	9.8	.48	3.76	6.20	9.96
Oct. 1920......	1.5	.3	2.0	.4	4.3	27.0	56.4	8.1	.48	3.56	6.49	10.05
Ave.	1.7	.3	1.9	.3	5.2	26.6	55.2	8.8	.49	3.26	6.75	10.01

Notes:

The high volatile coal mentioned above consists of about 75 per cent. of Eagle and about 25 per cent. of Elkhorn coal. The low volatile consists of about 85 per cent. New River and about 15 per cent. of Pocahontas coal.

The yield of gas is expressed in thousands of cubic feet per ton of coal as charged. The gas analyses are on samples taken after the light oil scrubbers. The amount of light oil removed was 3 gallons per ton of coal. The greater part of the light oil was recovered from the lean gas which was quite thoroughly scrubbed, whereas the rich gas was only partially scrubbed. The rich gas was scrubbed by using the benzolized oil after the lean gas scrubbers.

The yield of gas from these ovens is lower than normal owing to the fact that they are operated on faster coking time than that for which designed and therefore under high chimney suction which causes leakage from the oven chamber into the flues.

TABLE 41.

Hours of Coking:		2	3	4	5	6	7	8	9	10	11
CO_2	Volume per cent.	3.3	3.0	2.3	2.5	2.2	2.0	1.4	1.9	2.3	1.3
C_6H_6	" " "	1.8	1.5	1.1	1.1	1.0	0.8	0.6	0.5	0.35	0.35
C_2H_4	" " "	4.0	3.5	3.1	3.2	2.8	2.5	2.5	2.0	1.75	2.05
O_2	" " "	1.05	0.8	0.6	0.6	0.5	0.5	0.2	0.2	0.2	0.1
CO	" " "	0.9	1.9	2.9	2.8	3.0	3.95	3.4	3.1	2.8	2.8
CH_4	" " "	36.65	36.1	34.5	34.5	33.6	32.4	33.65	33.45	31.2	32.4
H_2	" " "	42.5	44.6	48.8	47.8	50.1	50.75	53.65	50.55	47.1	51.5
N_2	" " "	10.0	8.6	6.7	7.5	6.8	7.1	3.6	8.3	14.3	9.5
Heating value (net) calories per cubic meter (at 0°, dry, 760 mm.)		5,402	5,271	5,086	5,071	4,971	4,802	4,906	4,797	4,324	4,583

Hours of Coking:		12	13	15	17	19	21	23	25	27	Fuel Gas
CO_2	Volume per cent.	1.5	2.0	1.9	1.8	1.1	1.05	0.8	0.7	1.0	2.1
C_6H_6	" " "	0.35	0.3	0.25	0.1	...	...	...	...	...	...
C_2H_4	" " "	1.85	1.8	1.8	1.9	1.2	1.00	0.6	0.3	0.3	1.8
O_2	" " "	0.2	0.2	0.15	0.25	0.15	0.05	0.05	0.1	0.3	0.6
CO	" " "	4.15	4.1	3.9	4.15	4.7	4.00	3.8	4.9	5.8	4.2
CH_4	" " "	33.4	32.45	33.2	30.6	26.1	21.15	18.95	12.2	4.7	26.2
H_2	" " "	50.65	49.75	53.4	51.6	55.75	58.95	61.9	67.0	70.0	51.7
N_2	" " "	7.9	9.4	5.4	8.6	11.0	13.8	13.9	14.8	17.9	15.4
Heating value (net), calories per cubic meter (at 0°, dry, 760 mm.)		4,660	4,530	4,665	4,369	3,978	4,487	3,412	2,960	2,419	3,964

Change in Gas during Carbonization Period. There is a progressive change in composition of the gas from each charge of coal in an oven or retort as the carbonization process goes on. This arises chiefly from the fact of the progressive increase in size of the layer of hot coke through which the primary gases and tars pass. In another chapter—treating of the nature of carbonization—this phase of the production of coal gas is explained more fully. The practice of gas separation depends thereon, the early gases of the carbonizing period being richer than those of the later periods, so that if desired the early part may be separately collected and sold. In Table 41 [17] is shown the varying composition of the gas from a by-product coke oven, hour by hour during the coking period.

Sulphur. The gas when unpurified carries sulphur compounds, not only hydrogen sulphide, in considerable quantity (varying from 100 to 600 grains per 100 cubic feet) according to the kind of coal from which derived, but also an appreciable amount of the vapors of carbon bisulphide and other organic sulphur compounds, all of which contribute largely to the disagreeable smell of raw coal gas. Purified coal gas has still a sulphurous odor due to the difficulty of removing carbon bisulphide in the purifiers. In the gas as sold this constituent ordinarily varies from 10 to 30 grains per 100 cubic feet.

Light Oil Vapor. Coal gas, as usually distributed for public supply, carries more or less of the vapors of light oils (benzene, toluene, the xylenes) and of naphthalene. These materials although liquid (or solid in case of naphthalene) at ordinary temperatures, exert vapor pressures such that they may be carried in coal gas in important quantities at the usual temperatures at which a public gas supply is distributed, more in summer, less in winter.

By-product coke oven gas, made from a good coal or coal mixture of 30-32 per cent. volatile matter, carries at 75° F., when not debenzolized in scrubbers, 1.0 to 1.3 per cent. by volume, of these light oil vapors. This percentage is so far short of the saturation point at ordinary temperatures that condensation does not occur by cooling, except, for the average coal gas, in extremes of winter weather, and under high pressures. (See further on this, pp. 278-9, and W. H. Gartley, Proceedings Amer. Gas Inst. 1906, p. 593, "Delivery of Uniform Candle Power to the Consumer through all Seasons of the Year.") These constituents impart to the gas a high percentage of its illuminating power, and an important although considerably less percentage of its heating value.[18] The heating value (gross) of an average run-of-oven gas before debenzolizing is usually about 590 B.t.u. per cubic foot and after debenzolizing 555 B.t.u.

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[17] O. Simmersbach, "Investigations on the Temperature Relationships in Coke Ovens," *Stahl und Eisen*, 34, 954-958 (1914) (especially Table 2, p. 957).

[18] J. W. Shaeffer, in *Proceedings Amer. Gas. Institute*, 11, 514 (1916), reports the average loss of heating value from the gas at a number of by-product coke plants occasioned by scrubbing it for light oil to be 5.8 per cent. He suggests

In the making of coal gas and in its cleaning by the by-product recovery apparatus it is preferable to preserve a maximum of the light oils as vapor, rather than to permit their separation by solution in the tar. To this end, contact of the gas with tar, especially when cool, should be minimized throughout the train of by-product recovery apparatus.

Naphthalene. Naphthalene is a troublesome constituent of gas, in the distribution system, owing to its tendency to condense and clog the valves, meters, etc. It is therefore kept at a practical minimum. To avoid those conditions which produce it in the oven, or to reduce as far as possible its formation therein, abates more effectively the naphthalene evil than any efforts to remove it after once formed. Large, highly heated surfaces, flanking open space in the retort, with resulting increase in time of contact of the gases therewith, have the effect of carrying the thermal decompositions and condensations of hydrocarbons beyond the desirable stage and forming the double-ring and triple-ring compounds (naphthalene, anthracene, etc.) and carbon, free hydrogen and other gases.[19]

Owing to vapor pressure relationships and the miscibility of naphthalene with the light oils, less naphthalene will be carried in the gas if light oil vapors are present than in a "debenzolized" gas. (See reference above, to W. H. Gartley, Proc. Amer. Gas Inst. 1906, 593.)

Factors Influencing Yield and Quality of Gas. Temperature (at the walls of oven or retort) is perhaps the principal factor influencing gas yield and quality. The gas is formed mainly by thermal decomposition of the primary volatile products as they leave the uncoked core of raw coal and pass out through the hot coke and along the oven walls. Fully 60-70 per cent. of the volume of the gas results from this kind of decomposition and probably 50 per cent. of the yield of heat units in the gas per pound of coal. The degree of temperature affects greatly this decomposition.

Other factors are:

(1) The rate of flow of the gas through the heated coke and heated space above the charge—in other words the time during which the primary volatile products are subjected to the conditions of decomposition, a factor dependent in turn on width of the oven, its height and length, and on the amount of free space above the coal; full charges and narrow ovens make for reduced thermal decomposition, higher by-product yields and less free carbon and naphthalene;

(2) The ratio of heated wall area and of depth of coke in the

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a formula for calculation of this loss, based on the gallons of light oil removed per 1,000 cubic feet, (b): B.t.u. per cubic foot scrubbed gas $= \frac{a - 121{,}827\ b}{1 - 35\ b}$ in which (a) is the B.t.u. per cubic foot before scrubbing. The figures in this formula assume the production of 35 cubic feet of vapor per gallon of light oil and a B.t.u. value of 3,660 per cubic foot of this vapor.

[19] See article by Thos. D. Miller on "Naphthalene Formation in Coal Gas," *Amer. Gas Institute News,* Sept. 1917, pp. 416-36.

charge to the rate of production of gas per hour, these being the factors in which principally lies the difference between coke ovens, vertical retorts and horizontal retorts in their relative effect on gas yield and quality;

(3) The presence of a diluent gas, such as hydrogen (in blue water gas for example) or steam, either from without or from vaporization of water in the coal, which sweep out quickly the desirable gaseous constituents and by-products from the pores of the hot coke and the open spaces in the chamber, steam having a protective influence as regards the decomposing action of radiant heat, and hydrogen having both a high degree of diffusibility and a mass action in retarding, by its increased concentration, the decompositions which would tend to produce it. Steam is produced in the process of carbonization of the average coking coal, to the extent of 8 per cent. of the coal as charged, or probably ¼ by weight of the gaseous and vapor-form products leaving the retort. Its importance as a diluent and protective agency is thus apparent.

(4) The nature of the coal used, and its behavior in setting free, on primary decomposition, greater or less amounts of the paraffin hydrocarbons, the naphthenes, the oxygenated derivatives, or of water vapor.

Influence of the Type of Process and Retort Used. The form of coal gas common for city supply in the era now rapidly passing, when illuminating power in the open flame was the main consideration, is manufactured principally in horizontal retorts with small thin charges, highly heated. On account of the large ratio of heated surfaces and of hot unfilled space, to size of charge in this type of retort, much degradation of the hydrocarbons (and phenols) in the volatile matter takes place, forming carbon, anthracene, naphthalene, benzene, ethylene and other compounds of high carbon ratio, which impart a high illuminating value to the gas.

In the vertical retort and coke oven and in the full-charged horizontal there is less degradation of the volatile products into carbon and pitch, but, enough decomposition of the primary vapors into permanent gases to maintain the gas yield approximately equal to that of the old practice. The gas thus formed contains, however, less of the rich unsaturated illuminant hydrocarbons and more of methane.

The so-called "lean gas" from coke ovens, collected during the latter part of the coking period, is high in hydrogen, with a lower content of the hydrocarbons. It may have 80-90 B.t.u. less heating value per cubic foot than the average run-of-oven gas.

Yield of Total Thermal Units in the Form of Gas. In judging the performance of a coal in the manufacture of gas for public distribution, a very important consideration is the "make" of B.t.u. in the gas per pound of coal, in other words the product of volume made and heating value per unit volume. A gas of high content of hydrogen, and therefore relatively low B.t.u. value, may be formed in such relatively large volume per unit of coal, either by reason of the natu of the coal, or through the use of the expedient of "steaming" of tl charge (see pp. 364-7) as to establish a yield of total B.t.u. comparii favorably with that of the richer gases.

Practically, however, in the distribution of a public supply, as is explained more fully in Chapter 4, pp. 74-5, considerations of adde piping and power costs for distribution of the lower B.t.u. gases mal it necessary to limit the dilution of the gas in this manner.

In gas and coke manufacture under modern conditions and wit the prevailing grades of coal or coal mixtures in use, the yield of B.t. in the gas, without steaming of the charge, is from 2,800 to 3,400 pe pound of coal. Higher yields than 3,400 generally indicate excessiv degradation of tar vapors and primary gases by very high temperature with such formation of soot, naphthalene and pitch as to lower the overall efficiency.

Genesis of the Constituent Gases. *Methane,* or CH_4, most important as a heat-giving constituent in coal gas, is formed in som measure in the primary, early processes of decomposition; but i greater measure by secondary thermal decompositions, whereby for instance the early-formed higher members of the paraffin series of hydrocarbons and also, in the tar vapors, certain alkylated aromatics brea down into carbon, simpler aromatics and methane.

Ethane (C_2H_6) is rarely found in coke oven gas or in the gas fror horizontal retorts (unless charged full). It occurs generally, however in the commercial gas of vertical retorts to the extent of 1.0 to 3. per cent. The gas from low temperature carbonization carries ethan and some of its higher homologues in important quantities. Thes paraffin hydrocarbons result, in all probability, from the primary decomposition of complex alkylated, six-membered ring compounds i the coal, and from de-alkylation of higher phenols in the early-forme tars. Owing to their instability at the higher temperatures these hydrocarbons appear in the gas only from processes which expose a minimum of highly heated surfaces to the escaping volatile matter.

Hydrogen similarly results both from primary breaking down o the coal solids and from the secondary reactions induced by heat. A a temperature of 700°-800° C., the "cracking" of vapor-form hydrocarbon products from the primary coal decomposition, in such manner as to produce hydrogen, proceeds very rapidly, and there begins also at this temperature a rapid dissolution of the solid semi-coked residue generating hydrogen. It is not likely that coal contains any one class of constituents that characteristically excels in producing hydrogen, as a large factor in the final result, although it does appear probable from the results of researches in primary decomposition of coal that hydrogen in some small measure arises from the primary early decompositions.

Carbon monoxide and *carbon dioxide* are formed by breaking down of the oxygenated compounds in the coal, the former also in some measure by secondary reactions such as that of CO_2 with carbon, water vapor or the hydrocarbons. CO_2 is one of the earliest-formed primary decomposition products. As the plastic zone of fused coal recedes in the oven, generating CO_2 and water vapor, only a small part of these products issues through the heated coke zone, hence, successive analyses of the gas throughout the coking period (see pages 316-7, indicate little or no increase of CO. Most of the CO_2 and water vapor issue through the core of uncoked coal. CO_2 therefore gradually decreases as the coking proceeds and as the core of raw coal diminishes in size.

Benzene and its homologues, as well as *naphthalene,* arise largely from secondary decompositions, the former by hydrogenation of the phenols and the latter from unsaturated naphthenes in the early formed tars. Toluene and other side-chain aromatics undergo decomposition when subjected too long to high-temperature conditions.

The unsaturated hydrocarbons of high carbon content, *ethylene, propylene, acetylene,* etc., are formed by the breaking down of more complex hydrocarbons in reactions induced by high-temperatures and relatively long contact with highly heated surfaces. They are thus not produced as freely in the heavy full charges of coke ovens, as in the lightly charged highly heated horizontal retorts.

Nitrogen (in high temperature coal gas) arises chiefly from leakage of air through the retort wall. A small quantity, of the order of 1.0 per cent. by volume, is to be ascribed to the break-down of nitrogenous matter and the thermal degradation of ammonia and other primary products.

Coal Tar.

Description and Composition. The condensable products from the gas, other than water, comprise the tar, a mixture of very many different compounds.

As most commonly produced for the market at the time of this writing, tar is a product of high temperature carbonization. This tar differs in important degree, both as regards its physical characteristics and its chemical composition, from the tar of low temperature carbonization.

High temperature tar is a black, rather thick and viscous liquid at ordinary temperatures, 12 to 22 per cent. heavier than water, and, usually, becomes semi-solid when cooled to 0° C. Low temperature tar, on the other hand, is a relatively thin liquid, flowing readily at 0° C. and low in specific gravity, only 1 to 6 per cent. heavier on the average than water. The fractionation curves of the two tars, by distillation, are not greatly different, but the physical and chemical characteristics of corresponding fractions differ greatly.

Chemically, high temperature tar is made up chiefly of hydrocarbons, of which the solid aromatic form a large proportion, and with which are mingled 5 to 20 per cent. free carbon (so-called), 3 to 7 per cent. phenolic compounds and small quantities of liquid aromatics, nitrogen bases and sulphur compounds. Paraffin hydrocarbons and unsaturated compounds are in the main absent.

On the other hand low temperature tar contains no solid aromatics, almost no free carbon, a predominating quantity of hydrogenated ring compounds with paraffin side chains, and a large percentage (10 to 40 per cent.) of complex high-boiling phenolic compounds. Unsaturated compounds also are present in important amounts.

Low temperature tar is obtained in yields twice to three times as large as those of the high temperature tar, a fact showing the extent of the process of degradation of these early-formed tars in the high temperature carbonizing process.

A comparison of the characteristics of tars from low-temperature and high-temperature carbonization is given by Jerome J. Morgan, and R. P. Soule [20] as follows:

TABLE 42.

FRACTIONATIONS OF REPRESENTATIVE TARS.

Fraction, B. P. Range, Degrees C.†	Percentage of Total Weight Low Temperature Tar ‡	Coke Oven Tar §	Gas Works Tar ¶
20-173	0.64	0.70	1.19
173-237	9.19	8.27	9.22
237-281	12.50	12.44	10.12
281-315	6.94	6.21	3.78
315-326	2.90	2.53	1.93
Pitch (by difference)*	67.83	69.85	73.76
Melting point of pitch, degrees C.*	53	69	89
Crude Dry Tar:			
Specific gravity 15.5/15.5 degrees C.	1.0676	1.1845	1.2172
"Free carbon," per cent	0.71	6.93	20.1
Summary of Composition:			
Phenols, per cent	13.7		
Nitrogen bases	0.624		
Hydrocarbons:			
Cyclic (unsaturated)	13.4		
Naphthene (saturated)	2.8		
Paraffin (saturated)	1.6		
Pitch (at 326° C.)	67.83		
	99.95		

* It is to be noted, in making these comparisons, that while the distillations were carried to the same final temperatures, they were not carried to pitch of equal melting points.

† Temperatures corrected for emergent stem of thermometer.

‡ From 18-foot primary retort of "Carbocoal" process, Irvington, N. J. Temperature at wall 600° C. Using Pittsburgh high-volatile coal.

§ From Seaboard By-Product Coke Co., Kearny, N. J. (Koppers Ovens).

¶ From Consolidated Gas Co., New York, approximately equal proportions from horizontal and inclined gas retorts.

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[20] "Characteristics of Low Temperature Tars," *Chemical and Metallurgical Engineering,* 26, 923-928 and 977-81 (1922).

Another example of coke oven tar (an average obtained in Koppers ovens, by the Carnegie Steel Co., Clairton, Pa.)[21] is given in the following, the data of fractionation being roughly comparable with those of Morgan and Soule (see above), if we assume the temperatures in this case to be uncorrected:

TABLE 43.

COKE OVEN TAR (FROM STRAIGHT "KLONDYKE," PA., HIGH-VOLATILE COAL).

Specific gravity (at 15° C.)	1.156
Viscosity (at 60° C.)	140
B.t.u. per pound	16,200
Free carbon	4.25 per cent.
Sulphur	.55 per cent.
Fractionation:	
Water	1.25
Light oil (0°-170° C.)	.20
Carbolic oil (170°-230° C.)	9.48
Creosote oil (230°-270° C.)	10.08
Anthracene oil (270°-350° C.)	22.71
Pitch (at 350° C.)	56.28
	100.00
Coke residue, at 1,200° C.	16.98 per cent.

Table 44 gives further comparisons of tars from coke ovens, vertical retorts and horizontal retorts:

TABLE 44.

CHARACTERISTICS OF VARIOUS HIGH TEMPERATURE COAL TARS.

	Coke Oven Tar *	Vertical Retort * (Intermittent)	Vertical Retort ‡ (Continuous)	Horizontal Retort * (Stop-end)
Specific gravity (at 15.5° C.) (dry tar)	1.19	1.17	1.115	1.250
Viscosity, Engler (100 c.c. at 115° C.)	35 s.	38 s.	....	77 s.
Tar acids, per cent. (on dry tar)	2.9	5.5 †	....	2.4
"Free carbon" (insoluble in benzol)	7.0	7.8 †	6.9	26.9
Crude naphthalene, per cent. (on dry tar)	5.5	2.0	....	6.0
Water	2.0	5.4	2.5	5.0
Light oil, 0°-170° C.	....	....	3.1	....
" " 0°-205° C.	2.0	3.0	8.0	1.5
Middle oil, 170°-230° C.	....	....	16.9	....
" " to soft pitch	21.5	25.5	....	24.1
Heavy oil, to hard pitch	20.4	18.8	....	15.2
Final temperature of distillation, degrees C.	350°	330°	....	340°

* Data furnished by The Barrett Co., New York, N. Y.

† Another analysis furnished by C. H. Stone, Rochester (N. Y.) Gas & Elect. Corp., shows 12.0 per cent. tar acids, and 4.4 per cent. "free carbon."

‡ Data of Woodall-Duckham Continuous Verticals, as obtained in plants at Schenectady, N. Y., and Meriden, Conn., furnished by Isbell-Porter Co., Newark, N. J., and Meriden Gas Light Co.

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[21] F. F. Marquard, Yearbook of the American Iron and Steel Institute, 1919.

A recent careful analysis, made by methods of unusual refinement of a mixture of four representative coke oven tars has been reporte by John M. Weiss and Chas. R. Downs.[22] Table 45, quoted from thi report, presents the net final results of the investigation:

TABLE 45.

CONSTITUENTS OF COKE OVEN TAR. (Weiss and Downs.)

	Per Cent. by Weight of Dry Ta
Light Oil:	
Crude benzene and toluene	0.3
Coumarone, indene, etc.	0.6
Xylenes, cumenes, and isomers	1.1
Middle and Heavy Oils:	
Naphthalene	10.9
Unidentified oils in range of naphthalene and methyl-naphthalenes	1.7
Alpha-mono-methyl-naphthalene	1.0
Beta- " "	1.5
Dimethyl-naphthalenes	3.4
Acenaphthene	1.4
Unidentified oil in range of acenaphthene	1.0
Fluorene	1.6
Unidentified oil in range of fluorene	1.2
Anthracene Oil:	
Phenanthrene	4.0
Anthracene	1.1
Carbazol and kindred, non-basic, nitrogen-containing bodies	2.3
Unidentified oils, anthracene range	5.4
Phenol	0.7
Phenol homologs (largely cresols and xylenols)	1.5
Tar bases (mostly pyridene, picolines, lutidines, quinolines and acridine)	2.3
Yellow solids of pitch oils	0.6
Pitch greases	6.4
Resinous bodies	5.3
Pitch (460° F. melting point)	44.7
Total	100.0

In respect to the above analysis by Weiss and Downs, the authors state, "The results can be accepted with the usual reservations which all conversant with the tar industry make because of the variations in the raw material of the industry." This fact probably accounts for their finding of a percentage of naphthalene double that of the analysis reported on page 323, since the percentages of this constituent, and of the benzol-insoluble material—often called "free carbon"—vary greatly according to temperatures and to methods of operation in the coke ovens.

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[22] *Industrial and Engineering Chemistry,* 15, 1022-3 (October, 1923).

The work of Weiss and Downs was done on a large industrial scale in the early steps of fractionation, about 20,000 gallons of coal tar distillate oil being handled, the tar acids and bases removed by extraction, and the neutral settled oil (about 10,000 gallons) distilled "in the most refined type of vacuum column still." The distillate was collected in 100 gallon fractions and examined in the laboratory. Distillation losses were "eliminated by equation as the work proceeded."

It is a notable feature of these results that they show comparatively few compounds actually existing in the tar in appreciable amount, "not over one-quarter of those popularly supposed to be there." Phenanthrene (an aromatic hydrocarbon with ethylene linkage, ortho-diphenylene-ethylene $(C_6H_4CH)_2$) is found in the surprisingly large amount of 4.0 per cent., and the methyl- and dimethyl-naphthalenes and acenaphthene (ethylen-naphthalene) in an aggregate of 7.3 per cent. These data bring forward new information as to the large content of cyclic hydrocarbons with methyl and ethyl group linkages in coal tar.

The amounts as given are not to be taken as commercially recoverable, "as it would not ordinarily be practicable to refine oils to the extent necessary to obtain all of any given constituent."

Mechanism of Tar Formation. None of the constituents of coal tar probably exists as such in the coal. Tar is not, in a true sense, distilled from coal. It results more properly speaking from condensation of the liquid products of the decomposition of coal by heat.

Jerome J. Morgan[23] concluding from the results of his elaborate and thorough investigations of low temperature tars and the processes of carbonization, outlines the process of high temperature tar formation chemically as follows:

"(1) The decomposition of coal by heat to ordinary high-temperature tar is a progressive, step-by-step decomposition in which pyrogenetic syntheses play only a secondary part.

(2) Six-membered rings and their combinations characterize the entire series of decomposition products from coal to high-temperature tar. The decompositions are essentially reactions effecting elimination of side chains.

(3) The average molecular weight of the liquid products constantly decreases as the temperature of carbonization rises. This decrease is marked by the evolution of hydrogen, CH_4 and C_2H_6.

(4) The initial decomposition of the primary low-temperature tar is (a) loss of hydrogen from naphthenes, . . . (b) loss of side chains from phenols by hydrogenation . . . (c) loss of hydrogen from nitrogen bases. . . .

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[23] J. J. Morgan and R. P. Soule, *Chemical and Metallurgical Engineering,* **26,** 923-928, 977-981, 1025-1030 (1922). Authors' abstract of these investigations, *Chem. Abstracts,* **16,** 2592 (1922).

(5) Final decompositions are at a maximum between 700° and 800° C and are marked by (a) dehydrogenation and de-alkylation of the hydroaromatic unsaturated hydrocarbons and bases to form aromatics with elimination of hydrogen, CH_4 and other simple gases, (b) hydrogenation of phenols to aromatic hydrocarbons . . . (c) secondary pyrogenetic syntheses of higher aromatics from simple compounds.

(6) The phenols of low temperature tar are the principal source of monocyclic aromatic hydrocarbons. The unsaturated naphthenes of low temperature tar are the principal source of polycyclic aromatics."

The researches of Fr. Fischer and colleagues [24] at the Institut-Mülheim, along these lines has afforded excellent corroborative evidence on which an outline like that above of the mechanism of tar and gas formation could well be based.

In interpreting the theory, as above presented, of the degradation of primary volatile matter into high temperature tar, there must be borne in mind the physical character of the process of carbonization—as explained in another chapter (see pp. 87-91). The slowly contracting band of plastic coal, in initial stages of decomposition, receding from the hot walls of the oven, is always (until near the end of the coking period) at a low temperature (375°-500° C., or 707°-932° F.) and is therefore producing low-temperature tars and gases which it sends through the heated coke and along the hot walls to undergo the series of reactions above described.

Factors Affecting Yield and Quality of Tar. The factors enumerated in earlier paragraphs as affecting yields and quality of gas have, in some respects, a corresponding effect also on the tar.

The temperature of the retort walls, and the ratio of heated wall surface and depth of coke to the amount of coal carbonized per hour affect greatly the decomposition of early-formed, complex hydrogenated and alkylated derivatives, in such manner as to produce greater or less quantities of free carbon and solid aromatic hydrocarbons. These constituents pass into the tar, and when they are formed in large amount by high temperatures and large heated surfaces, render the tar heavy and thick, high in pitch content and low in phenolic compounds.

Differences in the type of coal affect the quality of tar, the higher-oxygen coals giving somewhat thinner and less degraded tars with higher content of phenols. This may be due, in part, to their property of producing, in carbonization, a large proportion of CO_2 and water vapor. The coals of low volatile matter produce less tar than those of higher volatile.

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[24] Gesammelte Abhandlungen zur Kentniss der Kohle," Franz Fischer and Associates, 6 volumes, publ. by Borntraeger, Berlin, 1923; *Brennstoffe Chem.*, 1, 4-6, 22-4 (1920); *ibid.*, 3, 65-72, 57-9 (1922); *J. Soc. Chem. Ind.*, 41, 207 A; *Brennstoffe Chemie*, 3, 289-92, 305-7, 307-10 (1922).

TABLE 46.

PARTIAL LIST OF CONSTITUENTS OF COAL TAR AND PRINCIPAL DERIVATIVES THEREOF.

High Temperature Tars *	All Coal Tars	Low Temperature Tars	Principal Commercial Derivatives
Pitch, hard	Pitch, soft and medium		Pitch coke Coke compounds Electrodes Briquettes Roofing materials Paving materials Waterproofing materials Paints
Naphthalene Methyl-naphthalenes, acenaphthene and closely related naphthalene compounds		Only very slight quantities, if any, of naphthalene or its compounds occur in true low temperature tar	Insecticides Indigo Eosin dyes Alpha and beta naphthols and other dye intermediates Various other dyes
Phenanthrene Fluorene Anthracene and closely related oils			Dyes Anthracene oil Wood preserving oils Anthraquinone Alizarine

* Constituents listed in this column approximately in order of quantity present.

TABLE 46—*Continued*

High Temperature Tars *	All Coal Tars	Low Temperature Tars	Principal Commercial Derivatives
	Tar acids: Phenol (somewhat lower in low temperature tar). Complex higher phenolic compounds (markedly higher in low temperature tar)		Carbolic acid Antiseptics Pharmaceuticals "Bakelite" and other condensite products Picric acid, explosives Salicylic acid, aspirin Creosote oil Disinfectants
Phenol	Cresols, xylenols and other phenol homologs		
	Tar bases (containing nitrogen) occur in both kinds of tar, but in larger percentage in ordinary high temperature tar. Pyridene occurs in both.		
Pyridene, quinoline, etc. Carbazol, other nitrogen compounds, not bases			
		Naphthenes (hydrogenated cyclic hydrocarbons)	Denaturants Disinfectants These fractions, in company with the creosote or tar acid fractions above listed, form disinfectants, antiseptics, and wood-preserving oils
		Alkylated naphthenes (with complex straight-chain groups attached to cyclic hydrocarbon groups)	
		Unsaturated hydrocarbons (chiefly of cyclic nature)	
Unsaturated hydrocarbons occur in small quantity in high temperature tar, but in large percentage in low temperature tar.			

* **Constituents listed in this column** approximately in order of quantity present.

Light Oil:		
Benzene		Motor fuel Synthetic phenol Drugs and photo-chemicals Aniline dyes Azo-dyes Benzidene dyes
Toluene		"T.N.T.," explosives Saccharin Benzoic acid Benzadlehyde, dyes Perfumes, medicinals
Xylene		Motor fuel Solvents for rubber, paints and organic material
Cumenes, etc.		Resins
	Paraffin hydrocarbons and their derivatives	
Solvent naphthas		Solvents Resins

* Constituents listed in this column approximately in order of quantity present.

The use of steam during carbonization induces the recovery of a somewhat higher yield of tar, less degraded into free carbon and other solids, possibly owing to the cooling of parts of the charge through which the tars pass, and to the carrying out of the vapors more rapidly from the region of decomposing conditions.

Full charges in horizontal retorts establish conditions making for better tar yields, of a quality thinner and less degraded than that obtained from carbonization of the shallow charges.

Principal Substances Occurring in Coal Tars. In Table 46 are shown many of the substances occurring in coal tars, arranged approximately in order of their importance with respect to quantity present, and grouped to show their occurrence in high-temperature or low temperature tars, or in both.

Ammonia and Other Nitrogen Products.

The method of formation of ammonia from the nitrogenous organic material of the coal and losses of ammonia by secondary decomposition in the retort are phases of this subject discussed in another chapter (pp. 97-8).

The nitrogen derivatives found in the products of coal carbonization are ammonia, cyanogen, hydrocyanic acid, pyridene and other bases, free nitrogen in the gas, and a solid compound of nitrogen remaining in the coke, probably a nitride of carbon or analogous compound.[25] Of these the only product commercially recovered in America, as a general rule, is ammonia. Pyridene has been at times recovered in small quantities from the tar and light oil, as have also cyanides from the gas on a small scale.

Importance of Ammonia as a By-Product. Ammonia is recovered either as its water solution (ammonia liquor), or as crystallized ammonium sulphate. Although by weight the yield of ammonia (NH_3) is small, namely 0.2 to 0.4 per cent. of the coal, its commercial value, considering coal carbonization as a whole, is such as to place it in strong rivalry with coal gas for the chief position in commercial importance among the by-products. Coal carbonization is the principal source of ammonia in the United States, and a large factor in the supply of all countries.

Distribution of the Nitrogen of the Coal. Under present conditions of average practice in carbonization only 12 to 20 per cent. of the total nitrogen of the coal carbonized is recovered as ammonia. This is due to the fact that a large part (45 to 60 per cent) remains fixed in the coke, unless liberated by the special process of steaming, and another large portion (15 to 35 per cent.) is liberated as free nitrogen partly from thermal decomposition of some of the ammonia first formed. The diagram (Figure 132) shows approximately the average distribution of nitrogen in coal carbonizing plants in this country, but is to be understood as representing the mean of results which vary somewhat widely in the different types of plant.

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[25] Terres, *Jour. Soc. Chem. Ind.*, June 17, 1917.

TABLE 47.

(See references, pages 99-100, Chapter 6, to various authorities.)

Total nitrogen in coal, 1.45 to 1.75 per cent.

	Percentage of Total Nitrogen
Nitrogen recovered as ammonia	18.0 per cent.
" " " cyanide	1.2
" " " pyridene and other organic combination in tar	3.3
Nitrogen, free in gas	27.5
" remaining in coke	50.0
	100.0

The coke ovens, as operated under modern methods, with tops maintained relatively cool and the coal charged high in the oven, secure yields of ammonia somewhat greater than that above indicated, namely the equivalent of 22 to 30 pounds ammonium sulphate per ton (from coal mixtures of 85 per cent. high volatile and 15 per cent. low volatile), or 0.275 to 0.375 per cent. ammonia based on the coal, thus averaging 20.3 per cent. of the total nitrogen. In vertical retorts without steaming the yield is somewhat lower than in best modern coke oven practice,

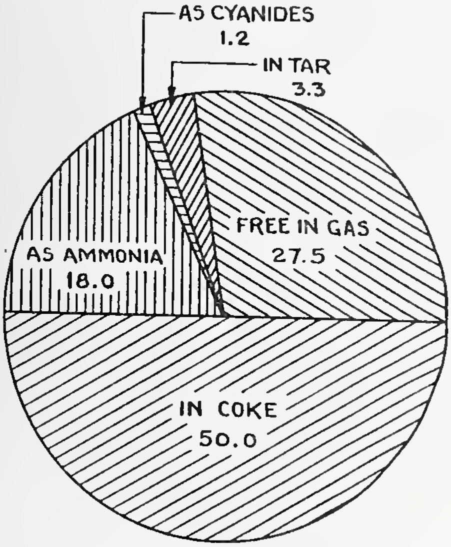

Fig. 132.—Approximate Average Nitrogen Distribution in High-Temperature Coal Carbonization (expressed in percentages on the total nitrogen of the coal):

but is in turn materially higher than that obtained from horizontal retorts.[26]

The decomposition of the nitrogen compounds of the coal is relatively slow until the temperature has reached 650° C. (1200° F.), that is, until the coal has passed the plastic stage, and ammonia then appears to be liberated principally between 700° and 850° C. (1290°-1560° F.).[27]

The main reasons for the low percentage conversion industrially of the total nitrogen of coal to ammonia may be set down as:

(1) Fixation in the solid residue, in a form of combination only slowly broken up by rise of temperature in a dry atmosphere, more rapidly in presence of steam;
(2) Thermal decomposition of ammonia, which, while slow in an atmosphere of moist coal gas without the aid of catalysis, is appreciable above 800° C. (1470° F.).
(3) Thermal decomposition of ammonia at 750°-850° C. (1380°-1500° F.), by contact with large surfaces, exposed by the coke and the refractory materials, especially if they contain iron oxides, as catalysts to the decomposition reaction. It is probable that this factor, in so far as the refractory walls are concerned, is offset in important degree by the rapid formation of a coating of carbon on the surfaces during carbonization.

In Chapter 6 experimental investigations are quoted throwing light on these influences.

Practical Expedients to Maintain Maximum Yield of Ammonia.

(1) Maintenance of oven top space as cool as is compatible with efficient practical coke production.

(2) Avoidance of the leakage of air into the ovens which would effect combustion and raise locally the temperature of the gases.

(3) Avoidance of too rapid a coking rate with the high temperatures necessary thereto.

(4) Use of coals with a minimum of iron in their ash, and of refractories presenting little if any free iron oxide for contact with the gas.

(5) Full charges, or a practical minimum of space left unoccupied in oven or retort above the charge.

(6) Uniform heats, rendering unnecessary the over-coking of some parts.

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[26] *Jour. Soc. Chem. Ind.*, **23**, 581.

[27] See Chapter 6, pp. 97-100, and the references to researches of O. Simmersbach and of J. W. Cobb.

(7) Steaming of the charge during the last fifth of the carbonizing period, that is, after all of the raw coal has passed through the plastic stage.

(8) Use of coal, in admixture, of a type bearing as high a percentage of oxygen as will not interfere with requisite quality in coke or gas.

Influence of the Type of Coal on Ammonia Yield. In general, the higher the percentage of volatile matter in the coal, the more ammonia may be expected. The percentage of nitrogen in the coal does not always influence the ammonia yield in direct proportion thereto but in general some influence is to be noted. Coals of the younger geologic formations, which as a rule are characterized by a higher oxygen-hydrogen ratio, produce on carbonization greater amounts of water vapor and carbon dioxide in the volatile matter, and owing possibly to the influence of these constituents a higher yield also of ammonia.

Cyanides. Hydrocyanic acid and cyanogen are formed in coal carbonization to an extent varying with the temperature and other conditions in carbonizing. In coke oven gas hydrocyanic acid occurs, equal to 60 to 90 grains per 100 cubic feet of gas, that is, 0.8 to 1.3 pound per ton of coal carbonized or about one-fifth of the ammonia formed. High temperatures promote cyanide formation; the presence of water vapor decreases it.

Bueb's process of recovery, now in commercial use at one of the largest American coal gas plants, treats the gas just after passing the tar extractors with a solution of ferrous sulphate alkaline with ammonia. A mixture of complex insoluble ferro-cyanides and ammonio-ferro-cyanides is obtained. The cyanogen (C_2N_2) in the gas at this plant (horizontal gas retorts) ranges from 80 to 120 grains per 100 cubic feet and the recovery is reported as over 90 per cent.

The commercial recovery of cyanides at gas works has not become general in the United States up to the time of this writing.

Pyridene occurs in small quantity in the mother liquor of the ammonia saturators, in crude ammonia liquor and in the first runnings of the light oil crude stills. It has been at times recovered commercially in America and sold as a denaturant for alcohol.

Benzols or Light Oil.

The condensable vapors, chiefly hydrocarbons, carried by coal gas as it leaves the ammonia scrubbing apparatus or saturators, and which are recovered by oil scrubbing as described, form what is known in the trade as "benzols" or "light oil." They consist mainly of saturated aromatic hydrocarbons of boiling points ranging from 65° to 180° C. (149°-356° F.). Depending on the method of manufacture of the gas they contain also unsaturated compounds and paraffin hydrocarbons.

Quantity of Light Oil Obtained in Coal Carbonization. There is a lack of agreement among published figures, given as representing the yields of light oil from coal gas and coke oven gas under American conditions.[25] It is probable that much of this lack of agreement arises from insufficient qualifying data as to conditions of manufacture, efficiency of plant, number of results averaged, etc., and as to content of impurities, particularly wash oil, in the various light oils.

Based on data of manufacture, at a large number of plants, obtained during and since the World War, particularly such data collected officially as part of the work of munitions supply during the War, a statement of average yields is here presented, representing modern conditions at American plants, operated efficiently but not with primary regard to light-oil recovery.

Average yields at coke oven plants have increased materially during recent years, as a result of careful attention to operating conditions and improvement of apparatus. The design of the ovens, temperature conditions in the oven, uniform heating, choice of coals, and the use of steaming of the charge contribute to increased formation of light oil vapors in carbonizing, while the minimizing of gas contact with tar, thorough cooling of the gas before scrubbing, and improved efficiency of scrubbing increase in important measure the percentage recovery from the raw gas.

Between 90 and 95 per cent. of the total "light oil" produced in coal carbonizing is recovered by scrubbing the gas, less than 5 per cent. is found in the tar, and the balance passes out with the scrubbed gas.

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[25] The following statement, arranged for ready comparison, presents figures quoted from various sources:

TABLE 48.

VARIATIONS IN LIGHT OIL COMPOSITION.

	Gallons Per Ton of Coal				Gallons Per Ton of Coal			
		Sperr [†]			Fulweiler [‡]			
	Sperr [*] Coke Oven	Coke Oven	Horizontal Retort	Vertical Retort [¶]	Coke Oven	Horizontal Retort	Vertical Retort	Püning [§] Average Coal Gas
Pure benzene	2.08	1.67	2.49	2.68	1.78	1.62	1.81	.6 -1.9
Pure toluene	0.56	.69	.54	.82	.40	.41	.43	.13- .46
Xylenes	0.32	....	....	....	....	....	....	.07- .23
Solvent naphtha	0.40	....	....	....	....	....	....	.08- .27
Naphthas (refined)	....	....	....	....	.22	.30	.41	....
Unsaturated hydrocarbons	....	....	....	....	.30	.36	.43	....
Other substances (principally hydrocarbons)	0.64	....	....	....	....	....	....	....
Total crude light oil	4.00	3.78	4.23	8.26	2.98	2.83	3.35	1.1-3.8

[*] F. W. Sperr, Jr., in "American Fuels," by Bacon and Hamor (McGraw-Hill Co., 1922), Vol. 1, p. 205, "typical coke oven light oil."

[†] F. W. Sperr, Jr., *Gas Age*, 41, 393 (1918). The figures in the original article are stated as yields per thousand feet of gas, and have here been converted approximately to yields per ton of coal by multiplying by 10.5.

[‡] W. H. Fulweiler, Chapter on Illuminating Gas in A. Rogers' "Manual of Industrial Chemistry" (3d edition), pp. 542 and 548.

[§] F. Püning, "Benzol and Its Recovery from Coal Gas," *The Gas Record*, 7, 173 (1915).

[¶] The remarkably high figures under this head, at variance with others for similar material, indicate some unusual conditions of manufacture.

TABLE 49.
LIGHT OIL YIELDS.

	Per Ton of Coal (Gallons) Coke Ovens †	Vertical Retorts ‡
Pure benzene	1.85	1.70
" toluene	.45	.55
Xylenes and light solvent naphtha	.30	.45
Acid washing loss (largely unsaturated hydrocarbons)	.16	.28
Heavy hydrocarbons and naphthalene *	.24	.24
Wash oil	.20	.38
Total crude light oil	3.20	3.60
Motor fuel fraction (purified)	2.50	2.55

* Naphthalene in crude light oil will vary from 1 to 3 per cent. by weight.

† Average conditions, modern plants, coal mixture of 85 per cent. high volatile, 15 per cent. low volatile.

‡ Average of continuous and intermittent, with high volatile gas coal.

Composition of Light Oil. The average composition of light oil from various sources is given in Table 49. The composition stated in column 1 represents more than 90 per cent. of the product in the United States. Many of the properties of the constituents of light oil are shown in Table 50 (quoted from Gas Chemists' Handbook, Amer. Gas Association, New York, 1922, page 287).

A number of compounds, not listed in Table 50, occur in crude light oil in small amounts. Among these are carbon bisulphide, pyridene and other nitrogen bases, and certain unsaturated oils which on distillation of the light oil become polymerized into gums or resins found in the still residue. Among these is the resin—*coumarone*—which has been extracted on an experimental scale with a view to commercial application.

Paraffin hydrocarbons, or saturated ring type compounds with paraffin side chains, occur in the light oil made under some conditions, rarely in that from coke ovens, frequently in that made in vertical gas retorts. Water-gas light oil (a product of the cracking of petroleum oils) also contains paraffins. They may vary from 2 per cent. in water gas light oil to 12 or 13 per cent. in the product of vertical retorts. For purposes of nitration, to produce, for example, tri-nitro-toluene, as a high explosive, the presence of more than 2 per cent. paraffins in the toluene is undesirable.

The difference in composition between the light oil from coke ovens and that from gas retorts reflects the difference in carbonizing conditions prevailing. The high temperatures and intensive "cracking" conditions that prevail in horizontal retort practice tend to reduce the proportion of toluene in the light oil and increase that of benzene and naphthalene. Researches by J. W. Cobb, with Hollings and others [29]

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[29] *Gas Journal* (London), 150, 588-91 (1920); see also Wm. Young Memorial Lecture, *Gas Journal,* 143, 482 (1918); also *Journal of the Chemical Society,* 107, 1106 (1915).

TABLE 50.

PROPERTIES OF THE IMPORTANT CONSTITUENTS OF LIGHT OIL.

Formula (molecular)	Carbon disulphide Data CS_2	Ref.	Benzene Data C_6H_6	Ref.	Toluene Data C_7H_8	Ref.	M-Xylene Data C_8H_{10}	Ref.	Naphthalene Data $C_{10}H_8$	Ref.
Molecular weight (O = 16)	76.12	1	78.05	1	92.06	1	106.08	1	128.06	1
Pounds per U. S. gallon (60° F.)	10.57	2	7.36	3	7.27	8	7.26	8	9.60	5
Specific gravity (0° C./4° C.)	1.2921	2	0 8999	3	0.8845	4	0.8823	8	...	11
Specific gravity (10° C./4° C.)	1.2773	2	0.8893	3	0.8757	8	0.8738	8	...	11
Specific gravity (15° C./4° C.)	1.2698	2	0.8839	3	0.8714	8	0.8697	8	1.1517	5
Specific gravity (20° C./4° C.)	1.2623	2	0 8786	3	0.8659	3	0.8655	6	...	11
Specific gravity (30° C./4° C.)	1.2473	2	0.8679	3	0.8573	8	0.8574	8	...	11
Expansion coefficient (° C.)	0.00125	2	0.0012	7	0.0010	7	0.00095	7	...	11
Boiling-point (760 mm. Hg)	46.2	1	80.36	12	110.3	13	139.1	13	217.7	1
Increase in boiling-point (°/mm. Hg)	0.041	14	0.043	15	0.047	15	0.052	15	0.059	16
Vapor pressure mm. Hg (0° C.)	127.9	14	26.63	18	7.20	18	1.75	18	0.022	9
Vapor pressure mm. Hg (10° C.)	198.5	14	45.68	18	13.02	18	3 45	18	0.047	9
Vapor pressure mm. Hg (15° C.)	244.1	14	58.90	18	17.22	18	4.74	18	0.062	9
Vapor pressure mm. Hg (20° C.)	298.0	14	75.21	18	22.53	18	6.43	18	0.080	9
Vapor pressure mm. Hg (30° C.)	434.6	14	119.34	18	37.46	18	11.43	18	0.135	9
Pound per cubic foot vapor (60° F.—30″)	0.202	10	0.209	10	0.244	19	0.281	19	0.339	20
Kg. per cubic m. vapor (0° C.—760 mm.)	3.42	10	3.54	10	4 14	19	4.76	19	5.72	20
Heat combustion (net) 15° C.—760 mm. Hg:										
Cal. per kg. liquid	3,480	10	9,960	17	10,150	17	10,230	17	9,700	17
Cal. per liter liquid	4,420	21	8,805	21	8,850	21	8,910	21	11,170	21
B.t.u. per pound liquid	6,260	21	17,930	21	18,270	21	18,410	21	17,460	21
B.t.u. per U. S. gallon liquid	66,100	21	132,100	21	132,600	21	133,500	21	167,300	21
Cal. per cubic meter vapor	11,550	21	33,600	21	40,150	21	46,500	21	52,400	21
B.t.u. per cubic foot vapor	1,300	21	3,780	21	4,500	21	5,210	21	5,910	21
Specific heat (Cal. per kg.)	0.240	23	0.419	24	0.440	24	0.383	25	0.314	26
Heat vaporization (Cal. per kg.)	83.8	27	92.9	27	83.55	28	78.25	28	...	11
Solubility in water (22° C.):										
Gm. substance in 100 gm. H_2O	0.219	22	0.072	22	Insol.	1	Insol.	1	Insol.	1
Gm. H_2O in 100 gm. substance	0.765	22	0.241	22	Insol.	1	Insol.	1	Insol.	1
Melting-point (° C.)	—108.6		+5.4							

REFERENCES TO TABLE 50

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2. Thorpe, *Chem. Soc. Journal*, 37, 364.
3. Biron, C. A. (1911), 609; *Chem. Zentr.* (1910), 1-1912.
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7. Castell-Evans, Physico-Chemical Tables, 1-151.
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19. Schiff, Ann. 220-91, Watt's Chem. Dict.
20. Calculated from theoretical.
21. Calculated from 10, 17, 19, 20, 27, 28, 2, 3, 5, 8.
22. Herz, Ber., 31-2670; Seidell, Sol. of Chem. Subst.
23. Regnault, Landolt-Börnstein, 771.
24. Schiff, Landolt-Börnstein, 767.
   Schiff, Physico-Chemical Tab. (Castell-Evans), 197.
26. Battelli, Landolt-Börnstein. 770.
27. Wirtz, Smithsonian Phy. Tab., 214.
28. Schiff, Physico-Chemical Tab. (Castell-Evans), 417.

NOTE:—References are, in many cases, to the fundamental data from which constants were calculated, i.e., (2) refers to relative volume data; (10) was computed from vapor density, molecular heat, etc.

have shown that benzene in an atmosphere high in hydrogen and containing methane is not appreciably decomposed at temperatures below 800° C. (1470° F.) but is freely decomposed at 900° C. (1650° F.), with deposition of carbon and formation of double- and triple-ring compounds. Toluene, he found, decomposed rapidly between 600° and 750° C. (1110°-1380° F.), and the presence of hydrogen in the gas did not retard this decomposition but rather accelerated it by the reduction of toluene to benzene and methane.

Application of Light Oil and its Fractions. The nitration of toluene to form tri-nitro-toluene ("T. N. T.") and of phenol (made from benzene to form picric acid, both used very widely as military explosives, for the bursting charge in shells, has given to the light oil of coal carbonization an extreme importance in war.

As motor fuel, replacing gasoline or mixed therewith, the redistilled and purified light oil (a mixture of benzene with 8-10 per cent. toluene and 4-6 per cent. xylenes) has abundant application. Its characteristics especially adapting it to this use are explained in Chapter 15.

Many and varied chemical derivatives, including pharmaceutical products and a large proportion of the so-called "coal tar" dyes are made from the purified fractions of light oil.

Factors Affecting Yield of Light Oil. Among the more important factors affecting practical recoveries are: (1) Nature of the coal, the coals of higher volatile matter as a general rule yielding more light oil, although other elements also have important influence. (2) Carbonizing conditions, moderately high temperatures being required, but, if too high (900° C. (1650° F.), or over in the oven tops), resulting in degradation to carbon and multiple-ring derivatives. (3) Temperature of the gas entering the scrubbers must be not above 25° C. (77° F.) for good recovery and preferably 20°-25° C. for high efficiencies. (4) The gas should have as little contact as possible with liquid tar in the train of by-product apparatus preceding the light oil scrubbers. (5) Wash oil of good quality (not too high in viscosity or emulsifying with water) is to be used in scrubbers designed to give it ample contact surface, and with a rate of circulation designed to produce not over 3 per cent. saturation of the oil. (6) The wash oil should be completely discharged of its content of light oil before recirculation and reduced to not over 5 per cent. naphthalene.

Chapter 12.

The Processes of Gas Manufacture by Coal Carbonization.

General. Other than by-product coke ovens, the coal carbonizing equipment used for gas manufacture comprises:

1. Horizontal retorts,
    (a) Stop-end type,
    (b) "Through" type.
2. Inclined retorts.
3. Chamber ovens.
4. Continuous vertical retorts.
5. Intermittent vertical retorts.

The distinctive feature of these systems of coal carbonization, as compared to by-product coke ovens, is the fact that each retort contains relatively a small amount of coal, in which the rate of coking is usually faster, and several retorts are grouped together in the same heating chamber or "setting." Such a group of retorts is called a "bench."

A bench of retorts, by way of further distinction, is heated by producer gas, often from a "built-in" producer. While the "secondary" air, used for combustion of this gas, is preheated in a measure by the heat of the waste gases, the heat recovery from the latter, being accomplished by recuperative, not regenerative, means, and without preheating of the fuel gas, is less thorough as a rule than in by-product coke oven practice. With use of waste heat boilers, however, in modern installations, the recovery reaches a high percentage. The retort gas is customarily not returned to be consumed, in part, in the setting as is commonly the practice in coke oven heating.

Vertical retorts, on the other hand, often permit recovery of the sensible heat of the coke for preheating air or for superheating the steam introduced at the close of the carbonizing period, in which particular they have gained a point of advantage over coke ovens. The continuous verticals gain in thermal efficiency also by decreasing the loss in sensible heat of the retort gases, by virtue of their passing through lesser sections of heated coke in the top portions of the charge, a further point of advantage over coke ovens.

Gas retort benches, grouping 4 to 16 retorts for heating in one setting, afford less opportunity for individual heat regulation, than does the coke oven surrounded by its own numerous heating flues each of which may be closely controlled in temperature. The retorts therefore do not produce, as a general rule, as uniform a grade of coke, suited as well to metallurgical use as do the by-product coke ovens (a relation governed also by the bulk of the charge and the carbonizing rate).

The retort, in comparison with the coke oven, is a vessel of smaller sectional area, the heat being applied on all sides instead of but two. The heat penetrates radially from all sides of an ellipse or D-shaped section, instead of in two directions only, from two opposite walls.

Horizontal Retorts.

Comment has been made in Chapter 3 (pp. 59-60) on the development of the various types of retort, and the reasons for their use in circumstances to which they are each particularly adapted.

The horizontal retort is not capable of the thermal efficiency that is attained in the verticals or in coke ovens, and its costs of operation are higher. But it continues to be installed nevertheless both in small plants where its flexibility makes it suitable to very small daily sendouts (as low as 75,000-80,000 cubic feet per day), and in plants where high illuminating quality in the gas is required.

In Figure 133 is shown a sectional side view of a bench of 9 retorts. Figure 134 is a view of the "through" type of horizontals. The placing of the producer directly under the setting, and the means of charging hot coke thereto may be seen. Frequently no provision is made for preheating the secondary air for combustion of the gas, but in the larger and more modern installations, this is taken care of by air flues in the setting deriving recuperation from the waste heat.

In modern plants waste-heat boilers are often used also with good results.

Small operations provide only hand charging and discharging, but in the larger plants, using "through" retorts, the charge is placed by a machine consisting of a collapsible scoop which can be withdrawn in small space above the coal, and the coke is discharged by a pusher ram.

For a description of a modern plant of horizontals, with modern appliances, large retorts and settings, and waste-heat recovery in boilers, reference may be had to a paper by R. G. Porter presented to the American Gas Association in 1920[1] on the "Horizontal Retort Plant of the Philadelphia Suburban Gas and Electric Co. at Chester, Pa." This plant has benches of 16 retorts, 8 high, and reports a variation in retort temperature—top to bottom of bench—of only 75° F. These retorts are D-shaped, 16 inches x 26 inches, and 16 feet long, taking a charge of 1,000 pounds of coal.

Horizontal retorts vary greatly in size and receive a charge ranging from 350 pounds in a 6-foot, stop-end, shallow-charged type, to 1,800 pounds in a 21-foot "through," full-charged type. Their carbonizing

[1] Technical Section Sessions, Amer. Gas Assoc., Vol. 2, 1920, pp. 84-95.

period is usually not less than 5 nor more than 12 hours. Periodical "scurfing" must be provided for, the burning out of deposited carbon from the walls, by opening to the air. The retorts, in modern installations, are built of silica shapes.

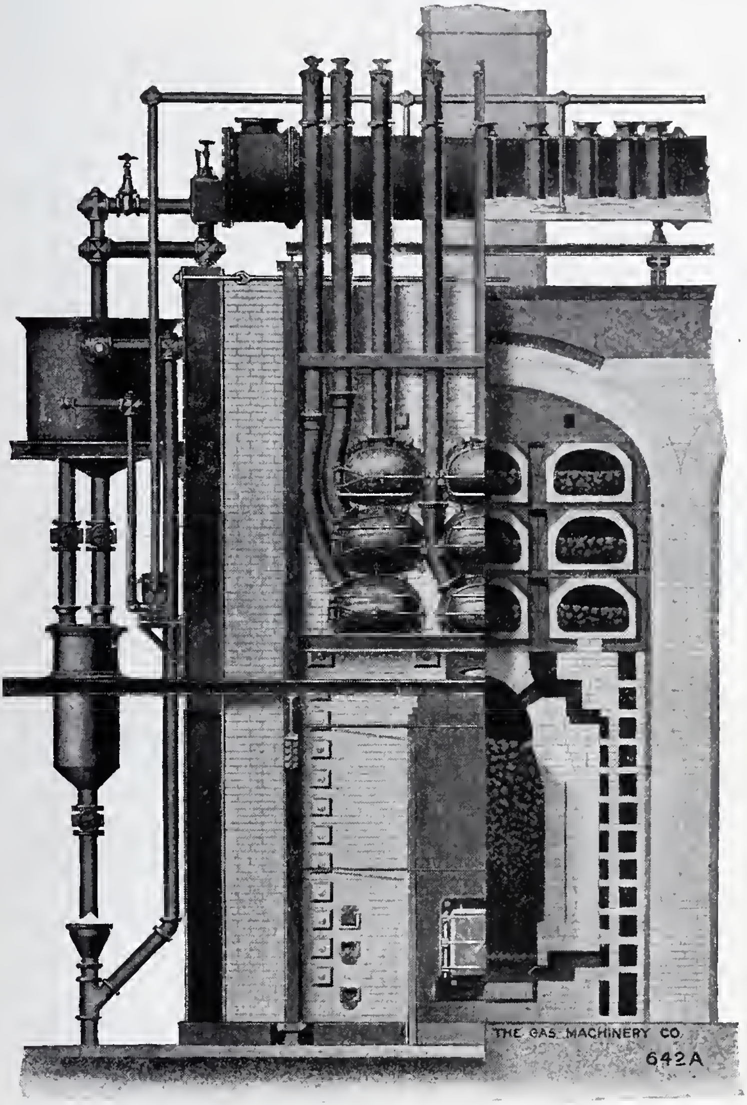


FIG. 133.—Bench of Nine Horizontal Gas Retorts, Transverse Section.

The effect of differences in depth of the charge on yields and quality of products has been explained in another chapter. Heavy, full-depth charges with a minimum of free heated space above the coal, make for better quality of tar, better yield of ammonia and less naphthalene.

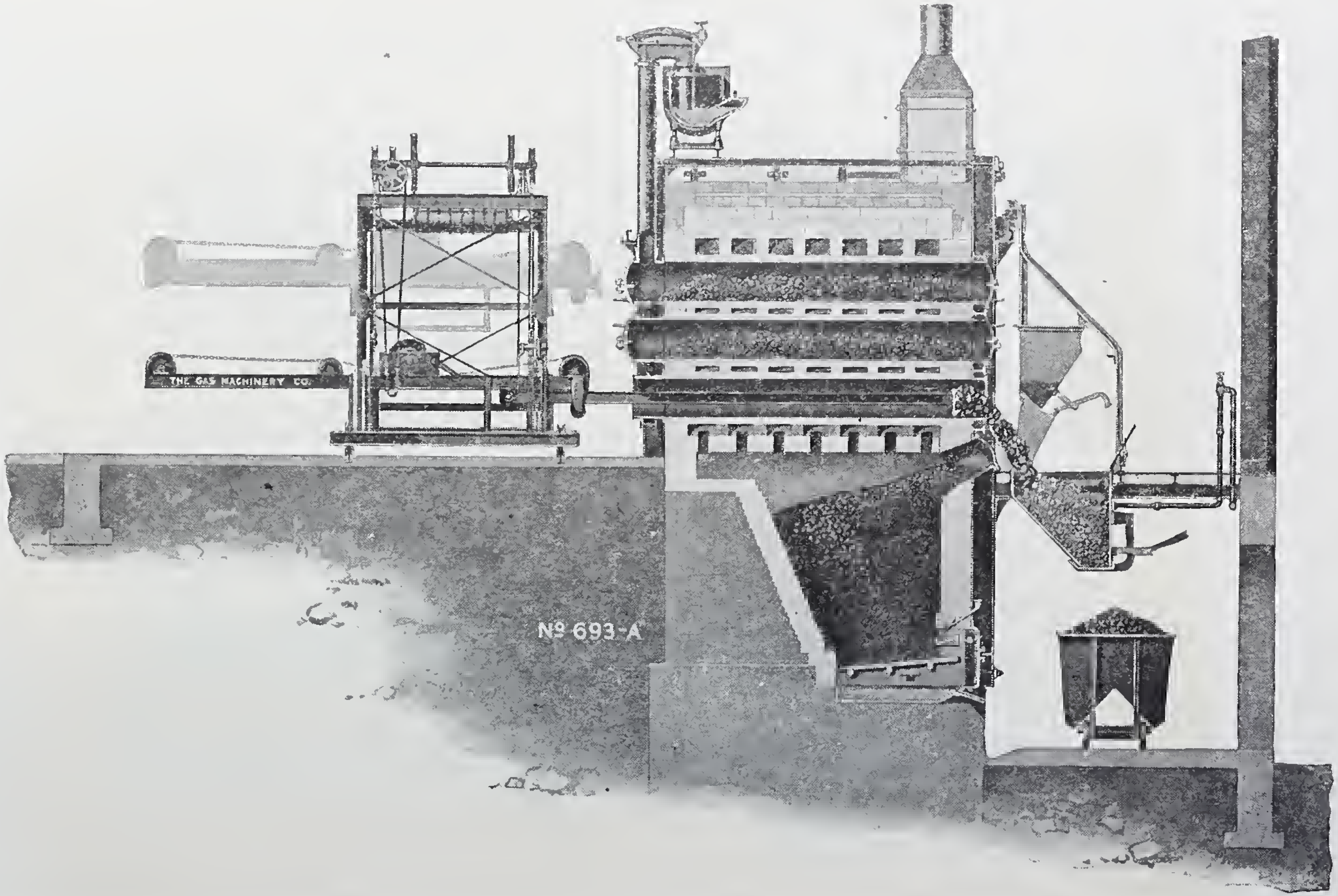
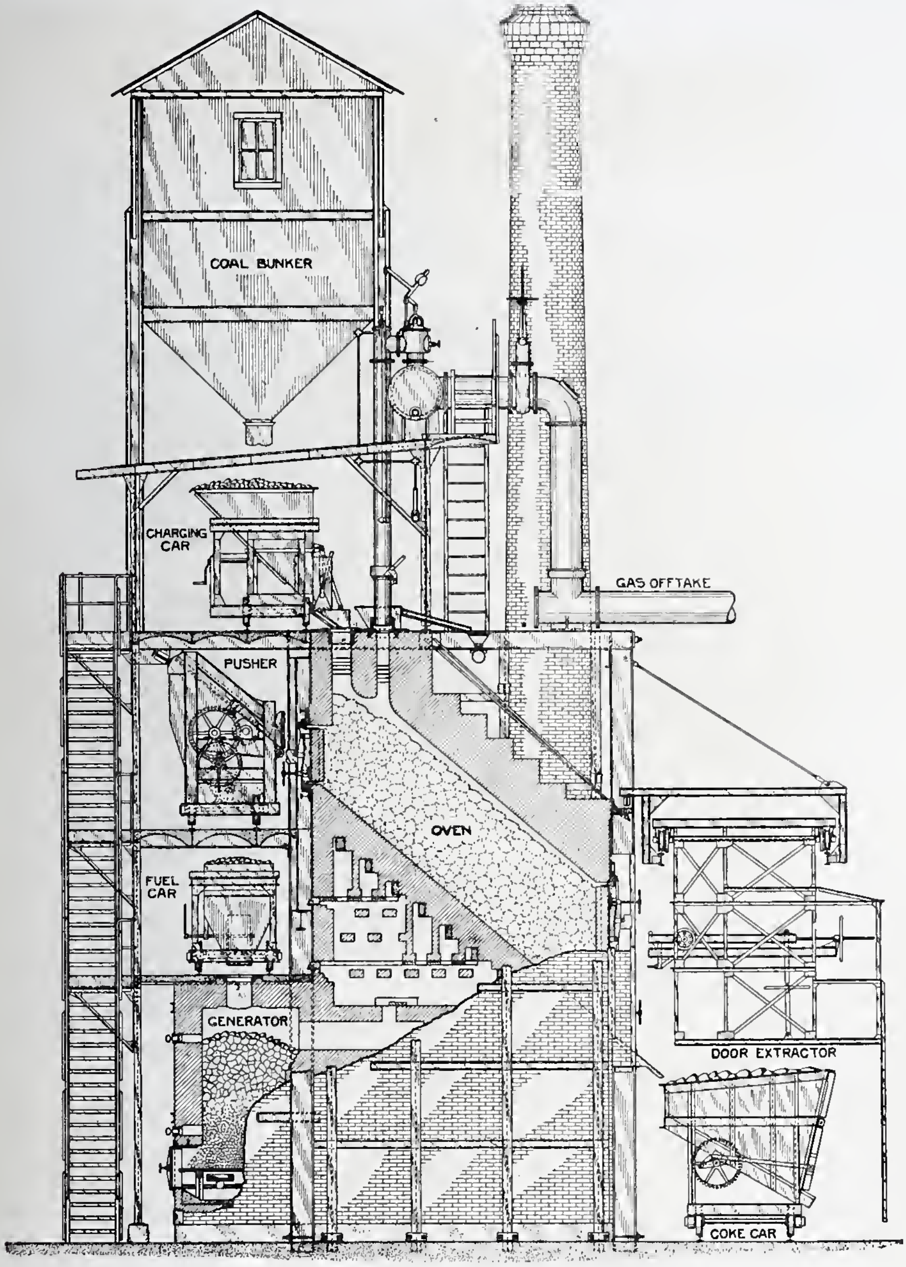


FIG. 134.—Bench of Horizontal "Through" Retorts, Longitudinal Section (showing discharging ram, gas-producer, etc.).

Inclined Retorts.

These are illustrated in Fig. 135. They have the advantage of a gravity discharge, and of full charges (except for a small volume of free space at the top as in vertical retorts).



The Gas Machinery Co., Etching No. 309.

FIG. 135.—Inclined Gas Retorts or Ovens, Showing Generator, Charging and Discharging Machinery, etc.

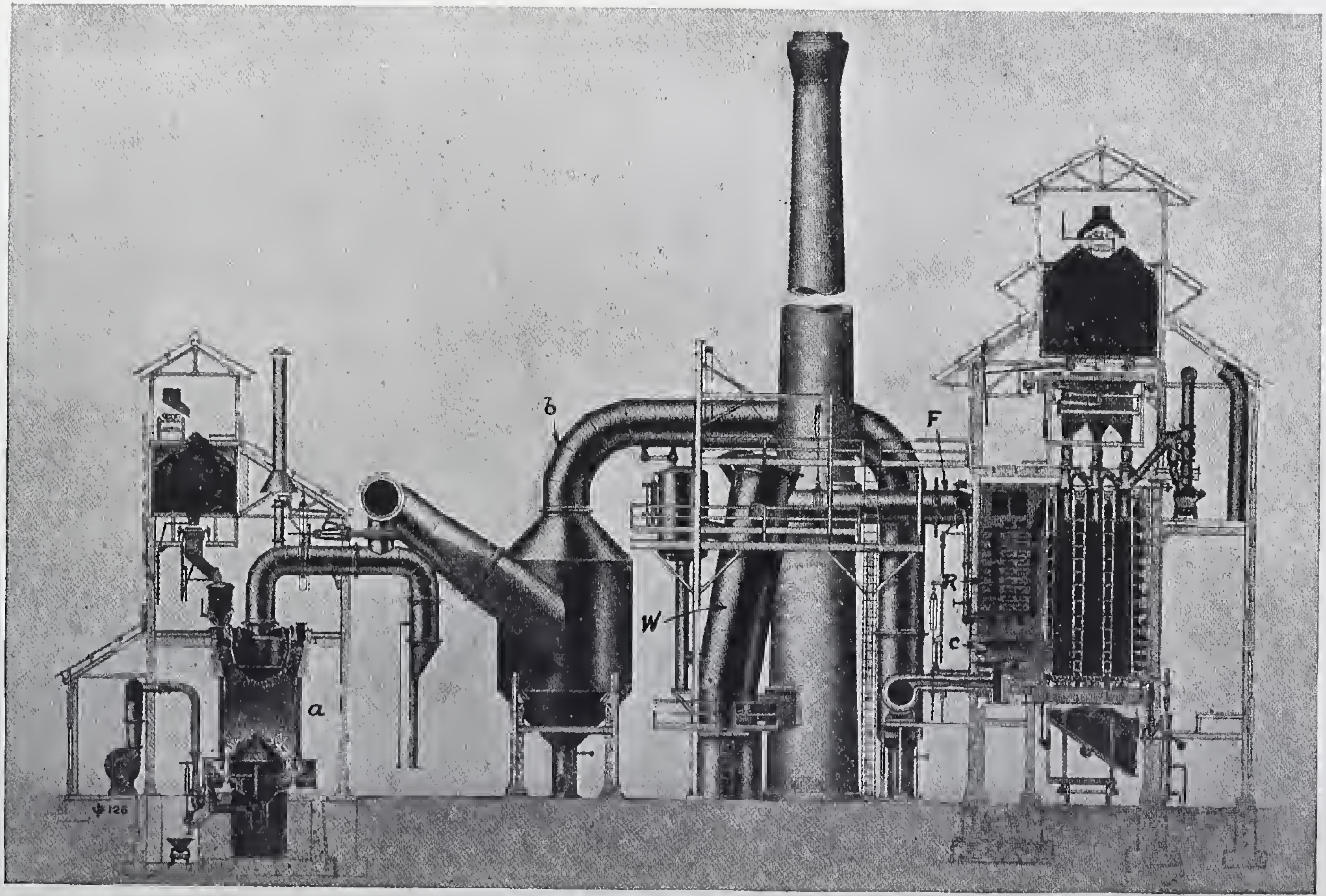


FIG. 136.—Vertical Gas Retorts of the U. G. I. System, with Detached Producer, showing arrangement of producer, cyclone dust arrester,

Vertical Retorts.

For carbonizing coal efficiently and with maximum recoveries of by-products, the various vertical retort systems of modern type stand in the front rank, and vie with coke ovens for supremacy in the art. Their heating efficiency, when the settings are designed and carefully built with that end in view, and when modern recuperators and waste-heat boilers are applied, stands at a high figure.

The smaller size of unit, as compared to coke ovens, is of advantage for flexibility, and the vertical position with gravity discharge makes for savings in operating costs. The larger operating unit of the coke oven system on the other hand makes also for economy of labor and in operating cost.

Vertical retorts have had their origin in Europe, the prevailing types chiefly in England, and while they have been modified and developed in American practice, in size, materials of construction, etc., they have had their greatest application up to the present time abroad. Their forte is in the making of gas, not coke, and for the latter there is a superiority in the greater bulk of the coke oven charges.

The trend of by-product coking toward the narrower oven and shorter coking periods—as making for increase of capacity and yields—has been anticipated by the vertical retort, whose cross-section is narrow, and whose essential principle is carbonization in multiplicity of small units in a common heat-setting, to secure a rapid penetration of heat through the charge, with a practical minimum of "cracking" in highly-heated space.

The Intermittent Type of Vertical Retort, Exemplified in the "U. G. I." System. An outgrowth in some degree of the Dessau system of intermittent vertical retorts developed in Germany, but essentially different in design, the U. G. I. retort is built in larger sizes, with silica materials, suited to the application of very high temperatures, and with recuperators to transfer 1/3 or more of the waste-gas heat to the air for combustion. A combustion space (c, Figures 136 and 137), adjoining, but outside of, the retort setting proper, is provided in the U. G. I. system, to improve the mixing of gas and air before entering the retort-heating flues.

These retorts are charged intermittently (about every 12 to 15 hours, according to the size) from coal larries running on a track above the battery of retort benches (shown in Figure 139). The retorts are generally three in a row, nine in a bench.

Coke is discharged, by gravity, into a coke car moving on a track beneath the retorts. When used in adjacent water gas generators or for other purpose near at hand, the coke is not quenched, but is screened hot and transferred direct.

Heating System. The benches may be heated either by "built in," attached producer, or by a central detached producer plant. The trend, in the more modern installations, is toward the latter plan, owing to

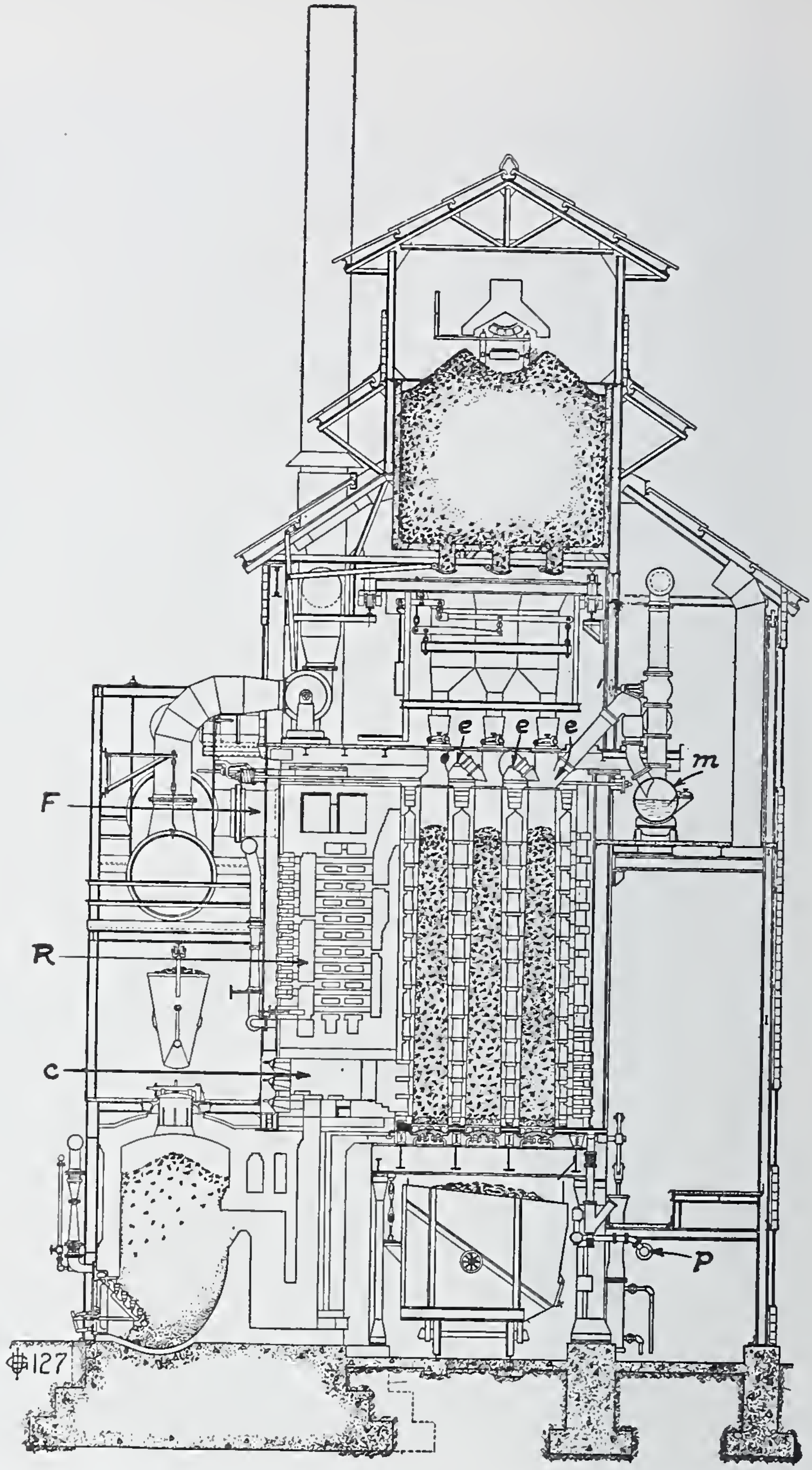


FIG. 137.—Vertical Gas Retorts of the U. G. I. System, with Attached Producer, Side View, in Cross Section, showing inside waste-heat boiler, arrangement of combustion chamber and heating flues, etc.

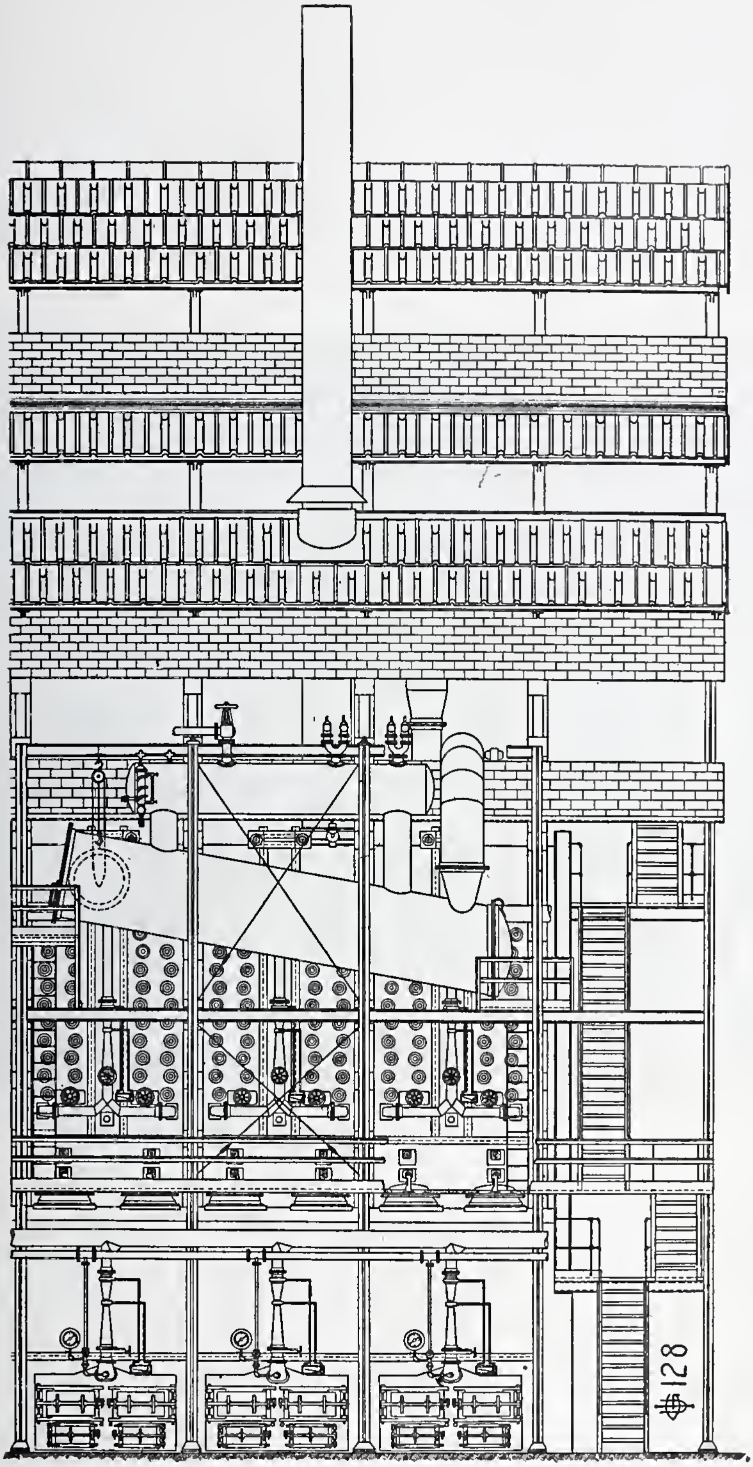


Fig. 138.—Vertical Retorts of the U. G. I. System, with Attached Producer, Front View, showing position of waste-heat boiler and operating floor above producers.

its large saving in labor of operation and its saving through the use of coke breeze and the finer sizes instead of the larger, more saleable grades of coke. With detached producers, operated on fine, low-grade fuel, dust removal from the gas must be provided for.

The illustration, Figure 136, shows the U. G. I. system with detached producer, cyclone dust arrester, and waste heat boiler. Figure 137 illustrates the attached-producer type of setting. The fuel-gas passes from the producer, (a, Figure 136), through the flue, b, into the combustion chamber, c, where it meets air preheated in the recuperator, R, above. The burning gases then pass around the lower portion of the nine retorts in the setting, and make their way upward, in 10 passes, back and forth across the setting (see Figure 137), until at the top of the retorts (Figure 136), they pass into the recuperator, R, and from this by the flue, F, into the waste heat boiler, W.

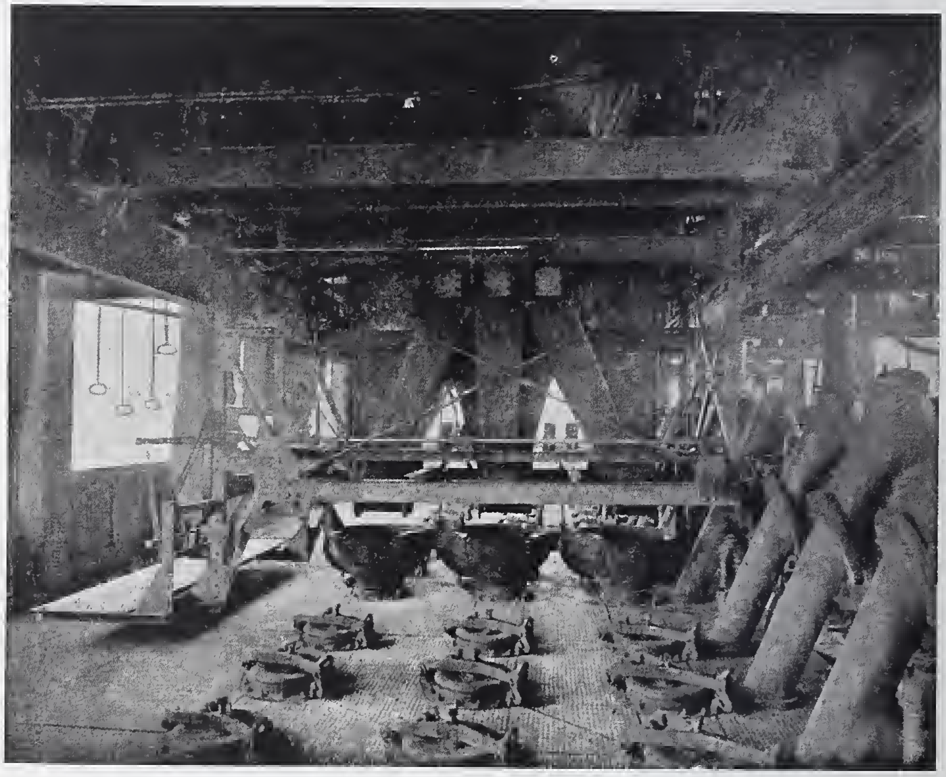


Fig. 139.—U. G. I. Vertical Retorts, View of Operating Floor above Retorts, showing coal-charging larry and off-take pipes.

The flue temperature at the bottom of the retorts is said to reach in some instances 2,700° F., and at the top is at 1,400° F. The waste gases leave the recuperator at 1,000° F. and the waste-heat boiler at 400°-450° F.

The temperatures may be varied under different local requirements.

The heat of the charge in the retort, or the amount of heated, open space where cracking of the gases occurs, may be varied to suit conditions.

Size and Shape. The retorts are of flattened elliptical section (Figure 140) and, in recent installations, 10 inches x 22 inches at the top, 18¼ inches x 30¼ inches at the bottom, and 22¼ feet long. Recently a larger retort has been designed, whose cross-section is one foot longer, thus increasing the size of a charge by 50 per cent., and the rate of output per day by 33 1/3 per cent. The charge in the usual 18 inches x 30 inches retort is ordinarily 2,000-2,200 pounds. The taper, widening toward the bottom, is to facilitate discharge of the coke.

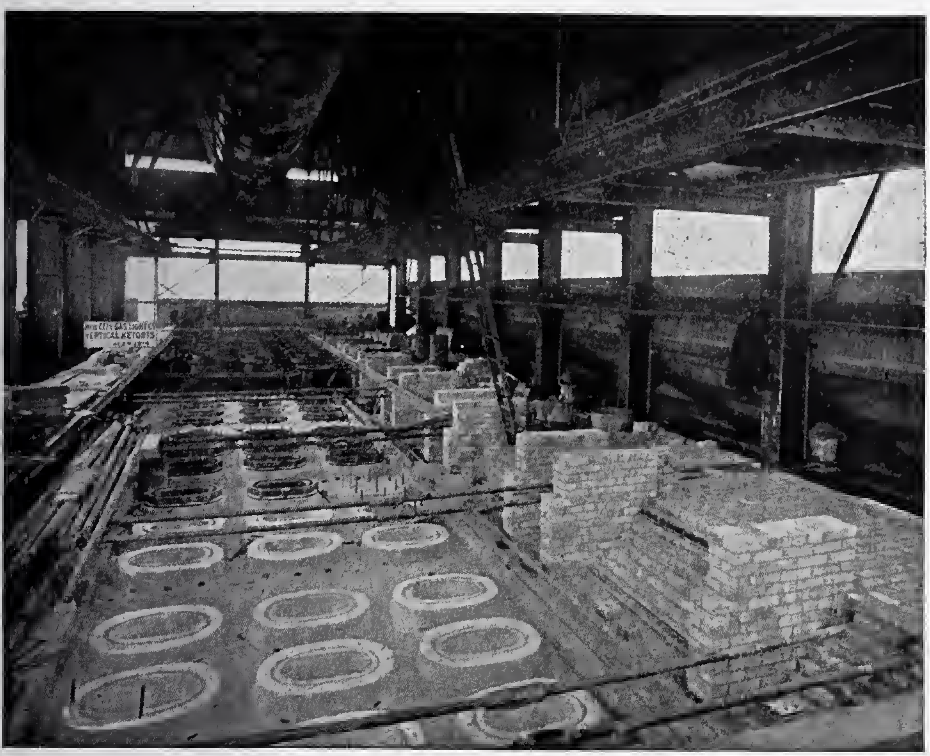


Fig. 140.—U. G. I. Vertical Retorts, Base of Retorts during Construction, illustrating elliptical section.

Scurfing of the retorts, or periodic burning off of the skin of hard carbon on the walls, is a process required in all gas retort operations. It is said to occasion in the U. G. I. system not over 3 per cent. lost time on a 12-hour carbonizing period.

Gas Outlets and Mains. The gas off-takes may be seen at e, e, Figure 137, and the hydraulic main (upper) at m. Figure 139 also, a view of the coal larry and upper operating floor, shows the standpipes and arrangement of off-takes. One off-take serves for a row of 3 retorts. The off-take pipes in the later installations do not dip under the liquor of the hydraulic (see m, Figure 137).

A lower gas take-off and a 10-inch main (shown at p, Figure 137) removes a part of the coal-distillation gas directly from the lower part of the retorts. This is designed to relieve the high gas pressure in the bottoms of the retorts. The tar collected in this main is of a quality differing markedly from that of the upper hydraulic. It contains, for example, very little free carbon and about 25 per cent. of tar acids, the average of all the tar having 12-15 per cent. of acids.

Producer Operation. In a report to the American Gas Association on producer operation in heating U. G. I. verticals at Rochester, N. Y.,[2] W. H. Earle presents a heat balance, from which the following summary is taken, showing fuel used per pound of coal carbonized, amount of heat recovered in boilers, lost in stack, etc. The producer fuel was coke breeze of 23.2 per cent. ash.

TABLE 51.

U. G. I. High Pressure Producers Heating U. G. I. Intermittent Vertical Retorts, Rochester, N. Y., for Month of April, 1920.

Total coal carbonized (dry)	12,391.2 tons
“ producer fuel used (dry)	2,106.2 “
(Pounds fuel used per ton coal	340)
“ volume producer gas	9,405,110 cubic feet
B.t.u. per cubic foot	128.5
Temperature at outlet of producers	1,050° F.
“ “ inlet to bench	1,020° F.
“ “ outlet of benches	1,150° F.
“ “ “ to stack	550° F.

Summary:

	Per Cent. Total B.t.u.	B.t.u. Per Pound of Coal Carbonized
Heat input to producers	100.0	1,940
“ lost in producers	11.6	227
“ “ “ producer flue	1.1	20
“ used in carbonizing	55.5	1,078
“ “ “ boilers	15.7	304
“ lost in stack	16.1	312

At another plant of U. G. I. intermittent verticals,[3] more recent than the one cited above, a recovery of 145 horse-power in the waste heat boilers is reported, on a daily carbonization of 175 tons of coal. The producer fuel used (dry, 17½ per cent. ash) is 373 pounds per ton of coal carbonized. This heat recovery is equivalent to 20 HP-hours per ton of coal carbonized, or 5.36 HP-hours per 100 pounds of producer fuel.

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[2] Technical Sect. Sessions, A. G. A., 1920, pp. 197-201.

[3] Article on Philadelphia Gas Works Vertical Retort Plant, by P. T. Dashiell, U. G. I. *Circle.* October, 1923.

Other data given on yields at this plant, for two months' operation are as follows:

	Per Net Ton Dry Coal
Coke	1,304 pounds
Tar (dry)	14.34 gallons
Gas (standard conditions)	12,069 cubic feet
B.t.u in gas per pound coal	3,288

The total power requirement is stated as 240 boiler horse power, or about 35 per cent. in excess of that obtained from waste heat of the settings.

There is to be noted here the distinction between the systems of heat recovery in coke-oven and vertical retort firing by producer gas. In the former, the waste heat of the firing of the ovens is recovered as pre-heat in *both* gas and air, while the waste heat boiler is applied only to recovery of the sensible heat of the producer gas before its delivery to the oven battery. This is in order to allow cooling and cleaning of the gas before use. In the latter system, however, that of the vertical retort heating, the waste heat of the setting is not recovered so largely in the secondary air, and the boiler is relied upon to effect 2/3 of the heat recovery. More producer fuel therefore must be used, and more steam is made (by waste heat).

By reference to Table 33, on pages 269-70, Chapter 10, it will be noted that results have been reported of the heating of coke ovens by producer gas, wherein 225 pounds of coke (195 pounds of carbon) were consumed in the producer per ton of coal carbonized, and steam, by waste heat, was made in the amount of 7.6 per cent of the producer fuel (or its heat equivalent) used. In the Rochester data on vertical retorts (Table 51, page 350) is shown a consumption of producer fuel of 340 pounds per ton of coal (23 per cent. ash and presumably about 75 per cent. or 255 pounds carbon), with a steam recovery by waste heat of 15.7 per cent. on the producer fuel. The net figures for fuel to the ovens are therefore not widely different in the two cases.

Continuous Vertical Retorts. As emphasized in a comparison of the systems of coal carbonization, in a previous chapter (pp. 59-60), the continuous vertical retort embodies, in theory, especial elements of economy and thermal efficiency. Automatic, continuous discharge of coke, the drawing down by gravity of a continuous in-flow of coal, with mechanical conveyance of both coal and coke to and from their reservoirs make for large economies in labor of operation. The recovery of the heat of the coke, either by pre-heat in the air for combustion or by direct action of steam passing through into the charge, makes for thermal efficiency, as does also in some cases a partial recovery of the sensible heat of the retort gas and vapors by a measure of cooling in the coal just below the off-take.

Certain practical difficulties, on the other hand, have been encountered, such as the detrimental effect of the mechanical discharge on coke quality, and, in some cases, irregular movement of the charge when the coal is highly coking in character. These difficulties have in modern practice been, in large measure, overcome.

The systems of continuous verticals used in America are the Woodall-Duckham and Glover-West. They differ somewhat in size of retort and mechanical operation, but mainly in the manner of applying the heats.

The Woodall-Duckham retorts are heated hotter at the top than at the bottom and the Glover-West the reverse. In the former the gas and preheated air enter at the tops of vertical flues surrounding each retort and burn downward, while in the latter the heating gases pass around the retorts, first somewhat above the bottom sections and, then pass to higher levels. The coke in the bottom is cooled by passage of the secondary air (for combustion) around the lower section of the retorts.

The purpose, in the Woodall-Duckham system, in maintaining higher temperatures at the tops, is to take care of the more rapid absorption of heat there by the cold coal, since at the lower levels, where coking has more nearly approached completion, it is claimed less heat is required. The net result of this method is to provide a more rapid carbonizing rate in the top sections than in the lower ones. The retort tapers to become wider toward the bottom, and therefore (see pp. 135-7) must offer in the lower sections greater resistance to the penetration of heat to the center of the charge. The carbonizing rate thus gradually decreases from top to bottom of the retort; the V-shape of the plastic zone in the charge is of a sharper angle than in those systems wherein temperatures are lower toward the tops.

The taper of the retort has been carefully worked out to suit these conditions and secure complete coking of the charge during its passage through.

This system, also, on theoretical considerations, appears to present, in the upper sections of the retort a larger zone of heated coke for cracking of the primary gases.

There is a range of 350°-400° F. between maximum and minimum temperatures in the flues. This, it is to be noted, is much less than the range between bottom and top temperatures in the U. G. I. intermittent retort, where a difference of 1,200° F. is often maintained. In the latter, however, the upper section—of 2 to 4 feet in depth—is not filled with coal, and the super-heating of gas and by-products in the free space is purposely restricted.

In comparing the heating system of the Woodall-Duckham with that of the Glover-West and U. G. I. retorts, a fundamental difference

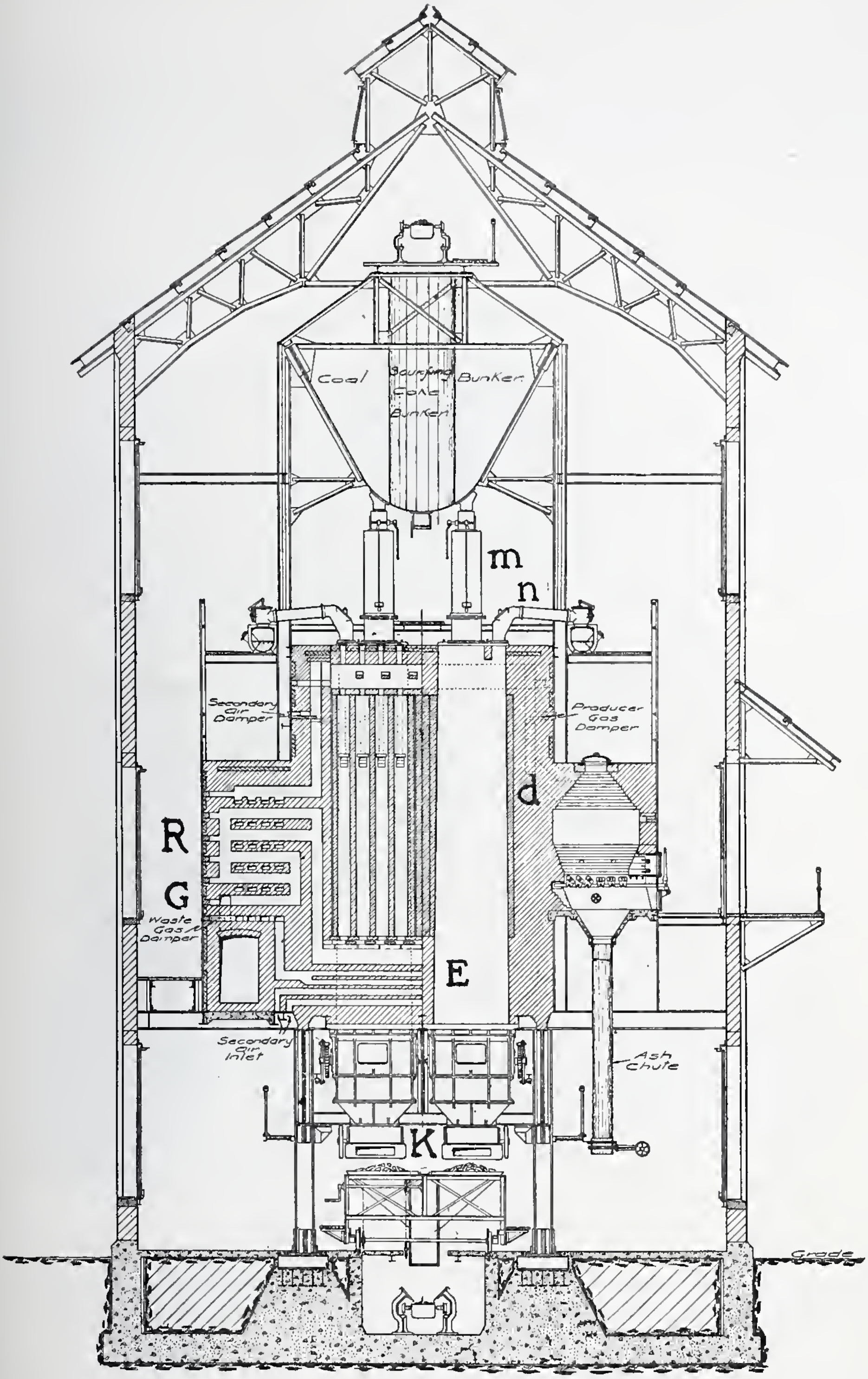

FIG. 141.—Woodall-Duckham Continuous Vertical Gas Retorts, Side View in Cross Section through the Flues.

in structure is to be borne in mind. The two latter types are elliptical in cross section, the peripheries thus being rounded, and on all sides flanked by heating flues. The Woodall-Duckham retort on the other hand is of rectangular cross-section, with heating flues on two sides only, a coke oven, in effect, set on end. The latter system, by reason of this structure, requires more intensive combustion in the flues to drive the heat into the coal, than is necessary in the retorts of smaller cross section entirely surrounded by the heat supply flues.

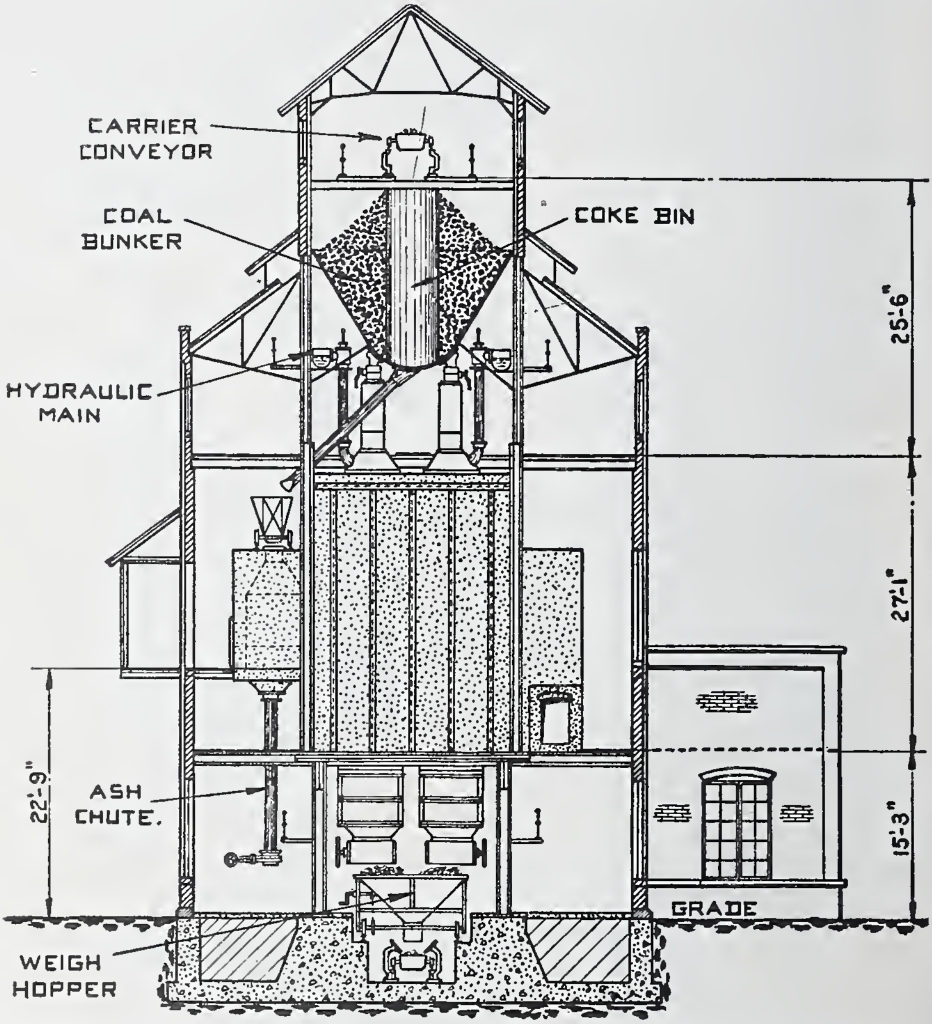

FIG. 142.—Woodall-Duckham Continuous Vertical Gas Retorts, Side View of Setting and Accessories (from side opposite to that of Fig. 141).

The Woodall-Duckham Continuous Vertical Retort System. The retorts are set usually 4 in a bench. Figure 141 shows a vertical section through the heating flues. The producer is indicated on the right, the hot gas passing through a duct, d, to the tops of the heating flues where it meets preheated air from the recuperator, R, and burns downward in the flues (4 on each side of each retort). About 5 feet above the bottoms of the retorts the waste gases unite in a horizontal chamber, from which they pass to the recuperator, and thence, through the damper, G, to the waste-heat boiler (not shown) and to the stack. At E are shown the heat-exchange air flues, surrounding the base of the retorts, whereby the secondary air is preheated by abstracting a part of the sensible heat of the coke.

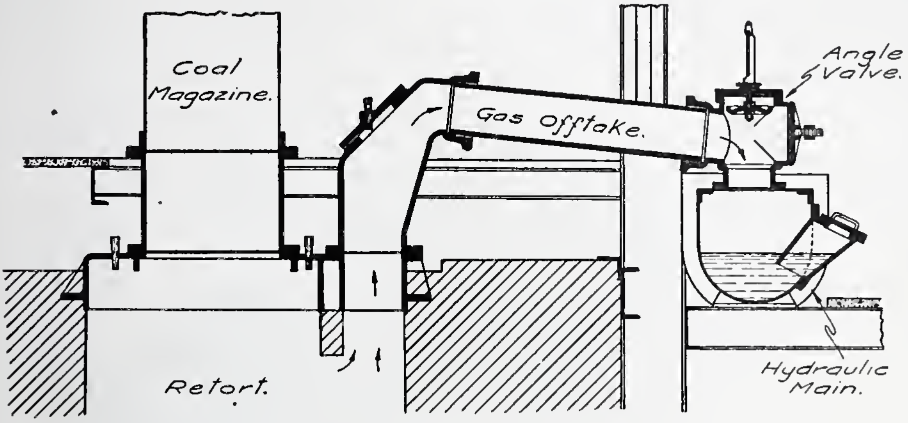

Fig. 143.—Woodall-Duckham Retorts, Detail of Gas Off-take and Hydraulic Main.

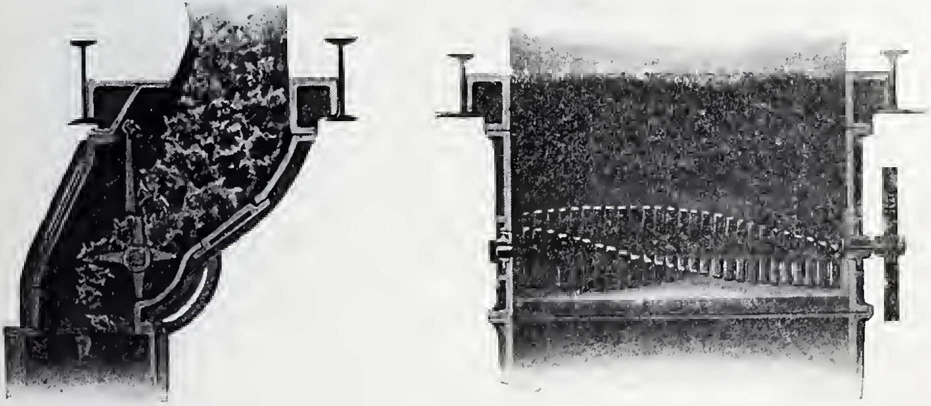

Fig. 144.—Woodall Duckham Retorts, Detail of Continuous Coke Extractor.

The coal magazine and gas off-take are at m and n respectively and the coke reservoirs at k, k. Detail of the gas off-take and main, the coke extractor (patented) and the coal feeding device is shown in Figures 143, 144 and 145-6, respectively. The doors at the top of the coal magazine and from the bottom of the coke reservoir are of gas-tight construction.

Figure 147 is a plan view of a plant of 4 benches, showing relative positions of the retorts and flues, hydraulic mains, coke bins and coal bunkers, the gas producers (1 for each bench) and the waste heat boiler.

The coke extractors are turned continuously at a rate suited to the make of gas required and the heats used. This draws the charge continuously downward. The coal magazines are refilled and coke reservoirs emptied by hand-operated valves about every two hours.

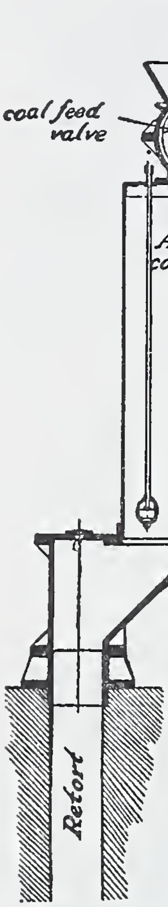

Fig. 145.—Woodall-Duckham Retorts, Arrangement of Coal Feed Device.

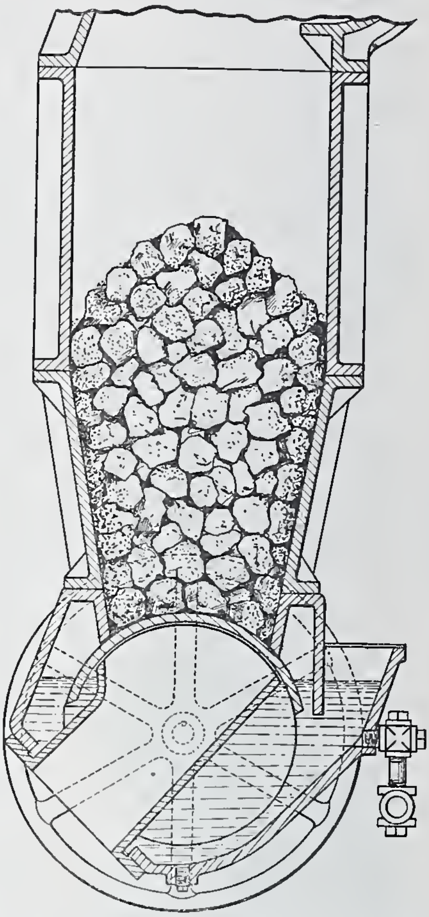

Fig. 146.—Woodall-Duckham Retorts, Detail of Coal Feed Valve.

The producers may be either attached to the setting or in a central detached plant. In the former case they deliver hot gas to the setting, but send dust also into the flues unless screened coke is used. The modern American plants use producers of ample capacity, in excess of the duty required, in order that in average running they may be operated at a low rate, avoiding clinkering.

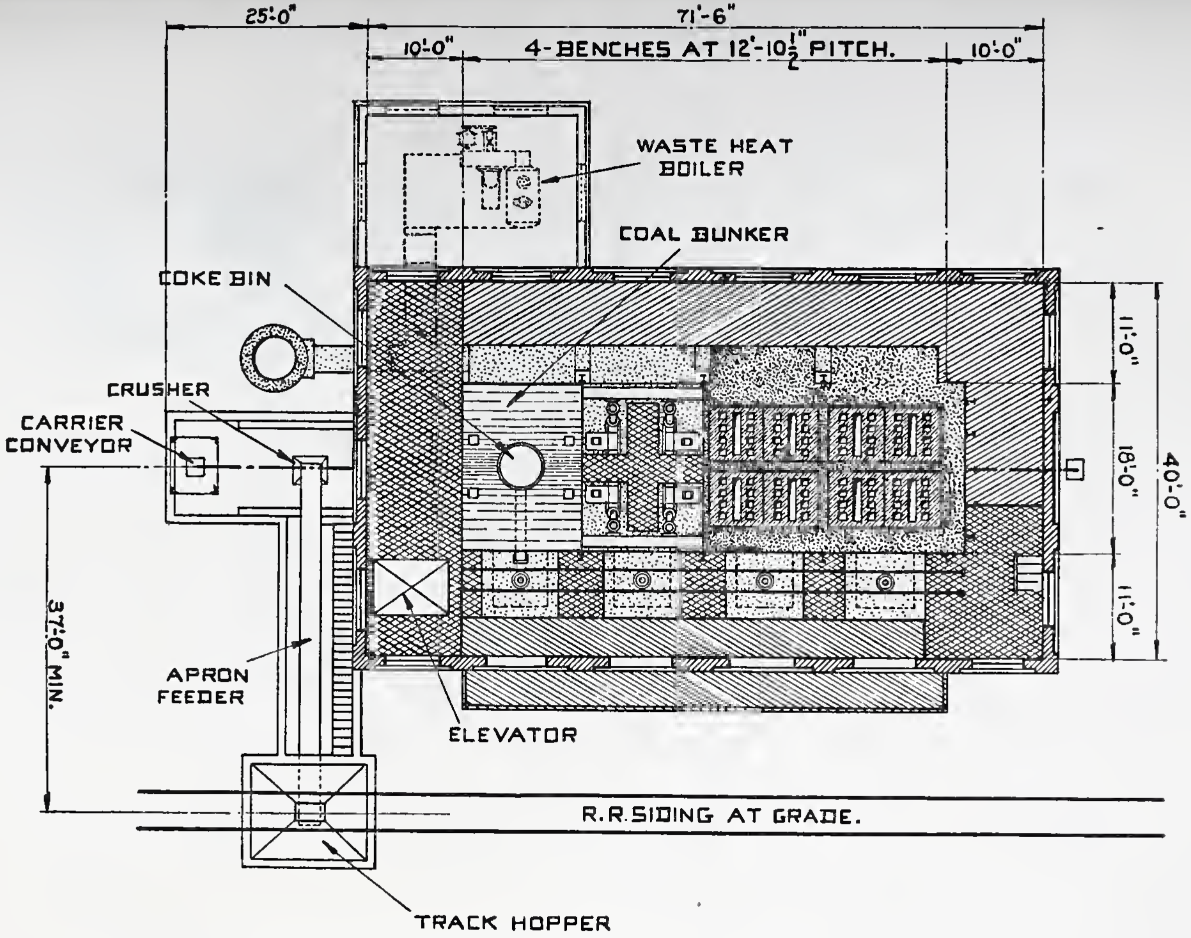

FIG. 147.—Woodall-Duckham Retorts, Plan View of a Plant of Four Benches of 4's.

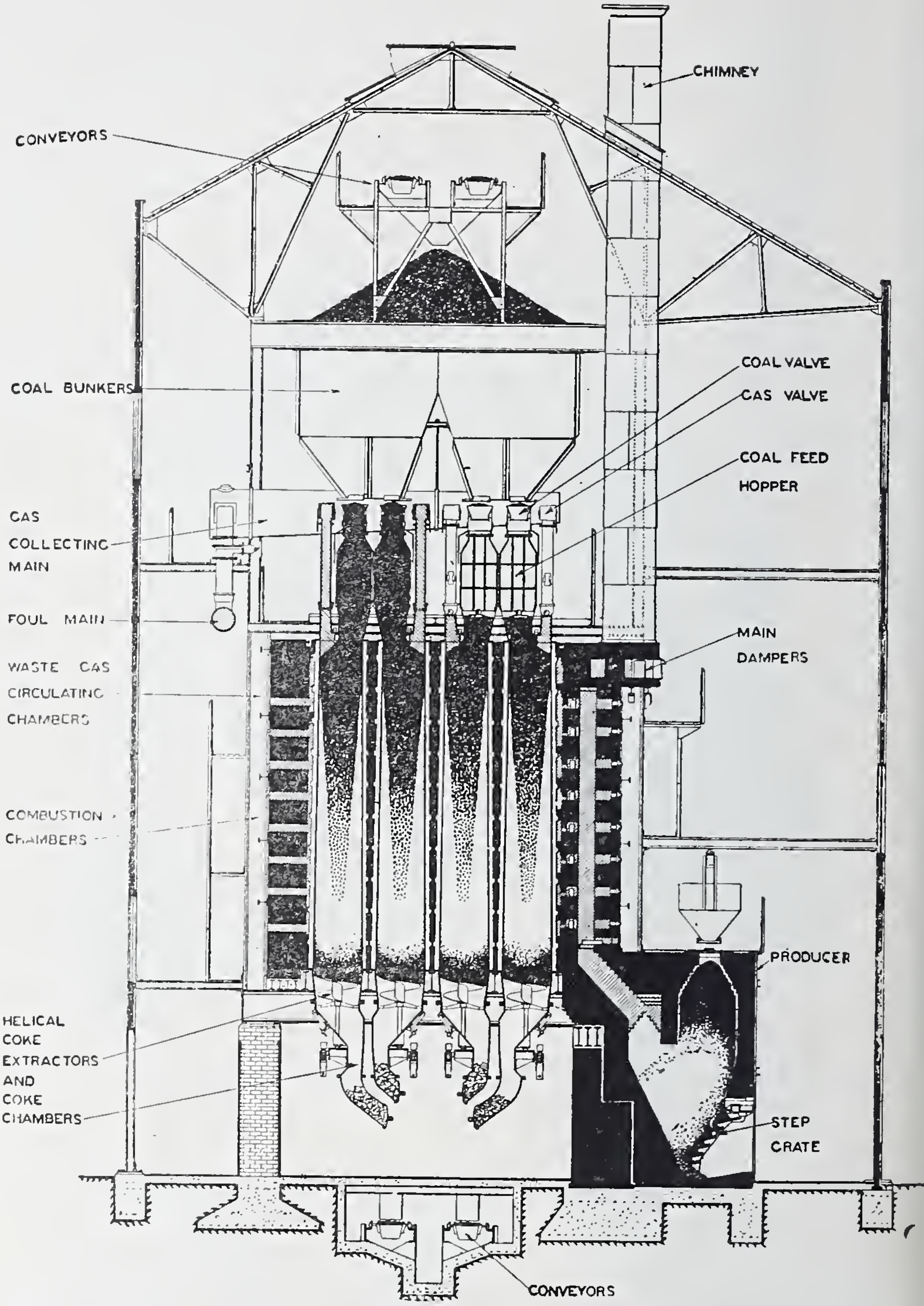

FIG. 148.—Glover-West System of Continuous Vertical Gas Retorts, Sectional View of a Setting of Four.

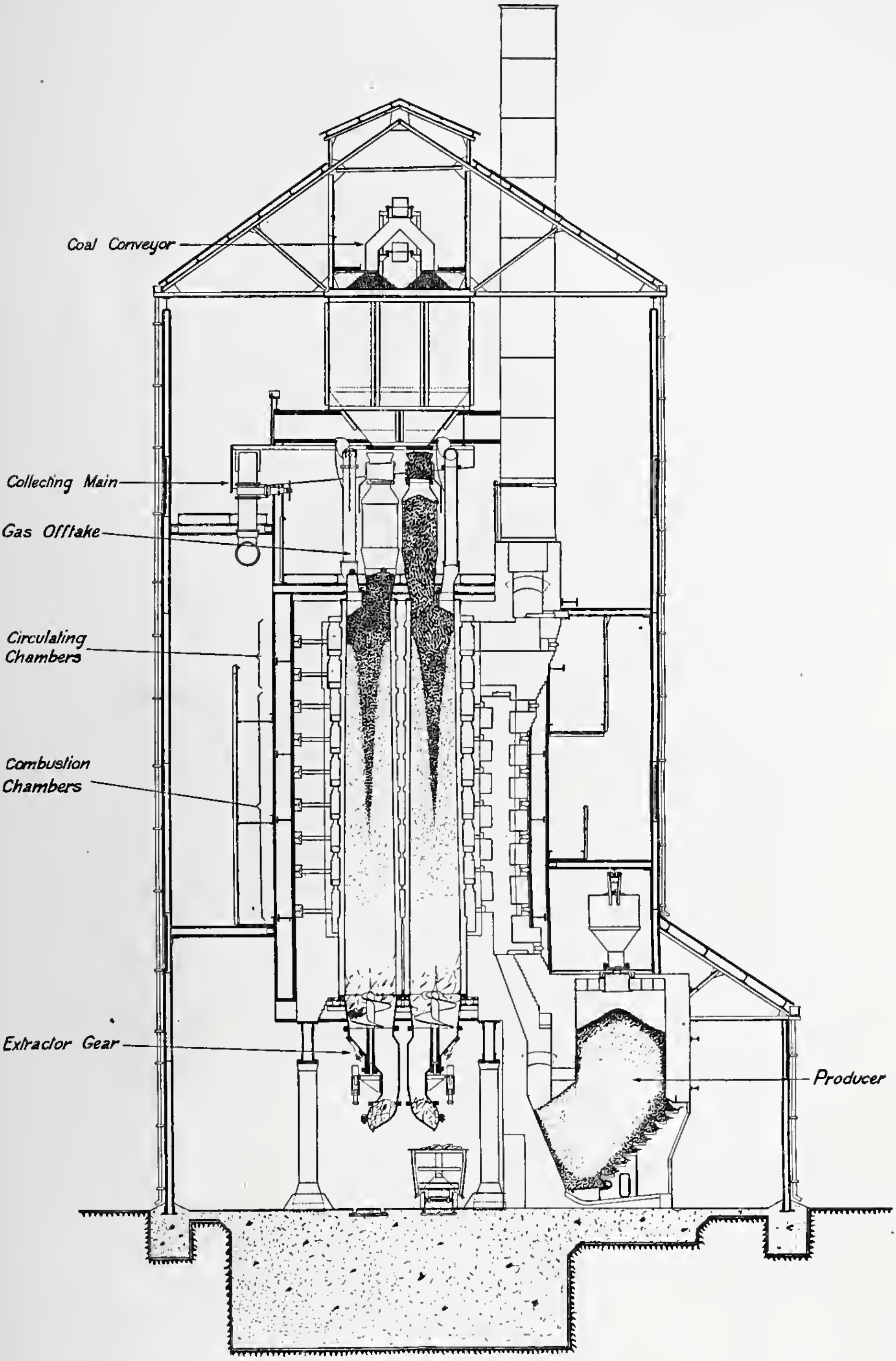

FIG. 149.—Glover-West Continuous Vertical Retorts, Sectional View of a Setting of Two.

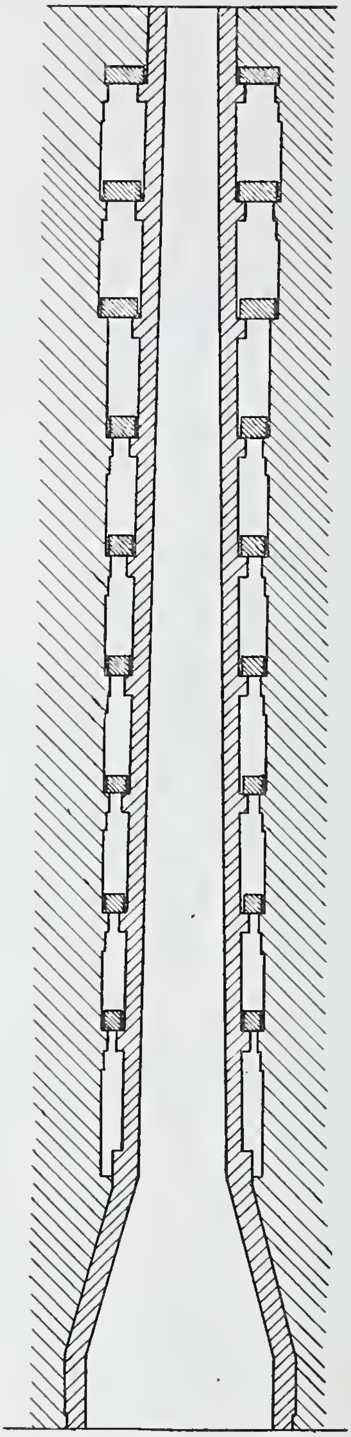

FIG. 150.—Glover-West Vertical Retort, Late Form, Cross-Section looking at Narrow Side to Show Flare at Bottom.

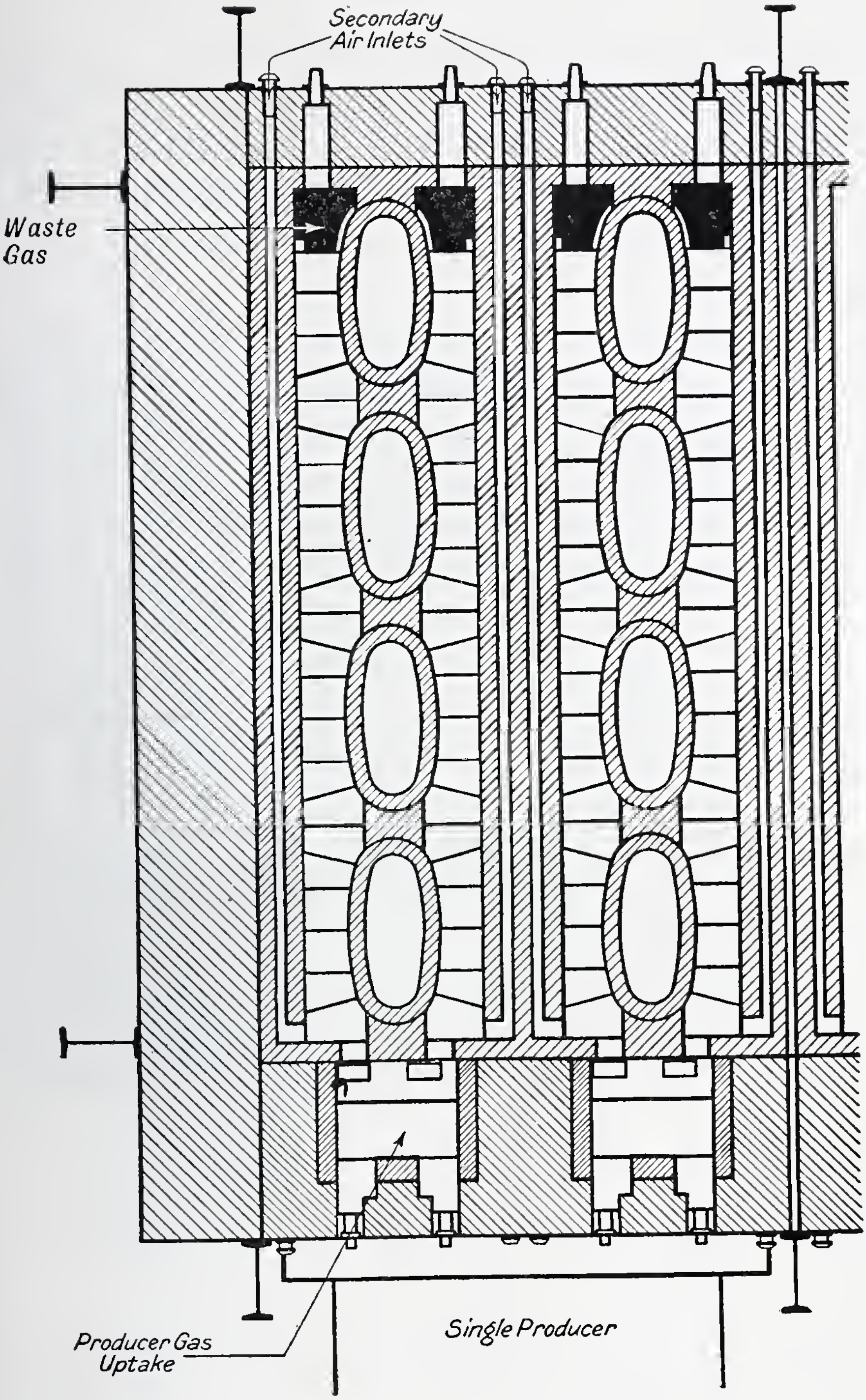

FIG. 151.—Glover-West Vertical Retorts, Horizontal Section of a Setting of Fours, Showing Secondary Air Inlets at Back Used when Steaming is Practiced.

On waste heat recovery from the setting, figures given the author by one of the larger recent plants of this system, show a recovery by the waste-heat boiler of 20 HP per bench (of 4 retorts), on a consumption of 280-300 lbs. producer fuel per ton of coal carbonized. This is equivalent to 19-20 HP-hours per ton of coal carbonized or 7 HP-hours per 100 lbs. of producer fuel used.

The daily carbonizing capacity of this retort, as built in America at this time, is 6 to 6½ tons. The dimensions of the later types are in general 9 inches by 48 inches at top, 20 inches by 63 inches at bottom, and 25 feet long.

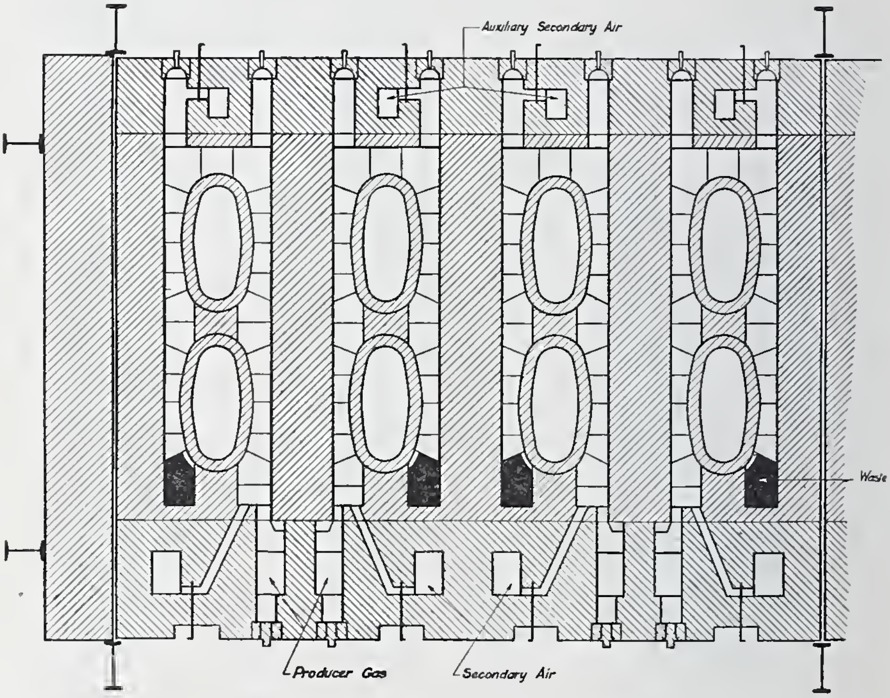

Fig. 152.—Glover-West Vertical Retorts, Horizontal Section of a Setting of Twos, showing Secondary Air Inlets at both Front and Back of Setting.

The Glover-West Continuous Vertical Retort System. As has been stated, these retorts are elliptical in cross-section, the later installations, however, having a "steaming section," 3 feet 3 inches long, at the base, which flares to a circular cross-section of 39 inches diameter (see Figure 150). An average of the later installations would measure 11 inches by 33 inches at the top, 18½ inches by 39 inches just above the "flare," and 25 feet in length. They are usually set 4 to 10 in a bench in two parallel rows (Figure 151), but special settings can be adapted for two (Figure 152) or even a single retort.

A distinctive feature of the Glover-West system is its provision for careful control of the heats in the separate, horizontal, superimposed heating chambers.

Figures 148 and 149 show the manner of heating the setting. From the producer gas uptake the gas enters 7 horizontal superimposed combustion chambers surrounding the retorts. Preheated air is admitted to these chambers at inlets adjoining the gas inlets. The burning gases pass across the setting to the back and upward *within the setting* to two additional horizontal heating chambers in which the waste gases return around the tops of the retorts and issue through the waste-heat boiler to the stack.

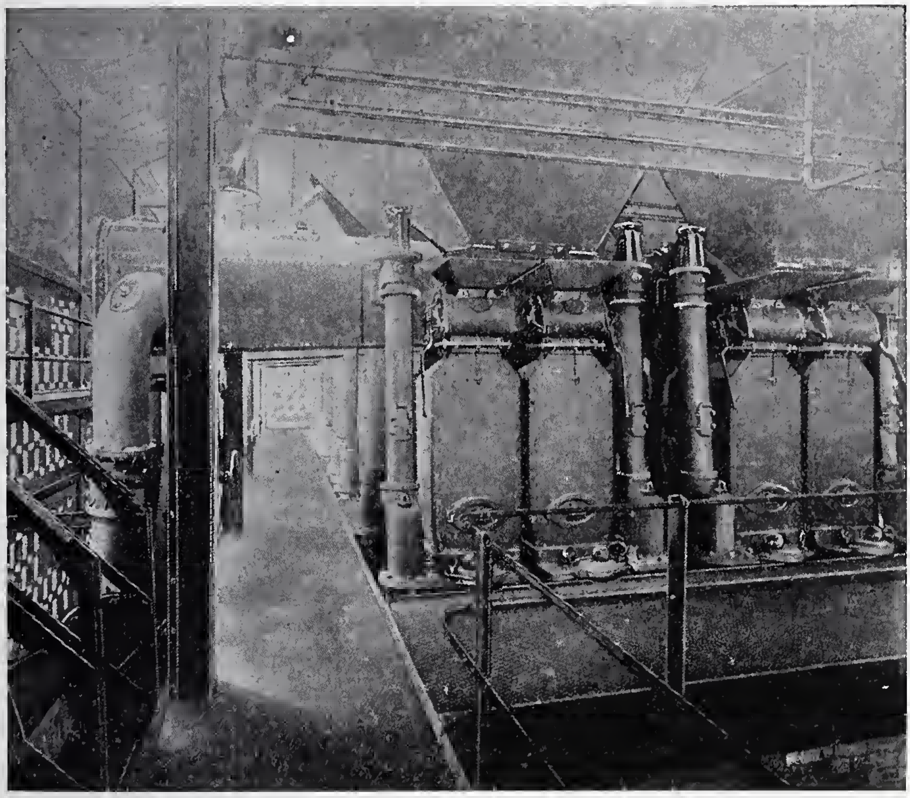

Fig. 153.—Glover-West Vertical Retort System, View of Upper Operating Floor, Coal Magazines and Gas Uptake Pipes.

The secondary air, when the practice of steaming of the retorts is *not* used, is passed in two lower chambers around the bottoms of the retorts, thus cooling the coke. It then passes up vertical flues in the front (or producer-side) wall of the setting, from which it issues into the combustion chambers. When steaming is used, it is not desirable to cool the coke (except by steam), and accordingly the secondary air enters vertical flues in the *back* wall of the setting, then traverses horizontal ducts in the division walls between the rows of retorts (Figure 151) and enters the front of the combustion chamber as before.

It may be seen that through the use of dampers and of varied gas and air supply to the ten separate, superimposed heating chambers, a thorough and flexible control of heating conditions is established. For this reason the Glover-West system was chosen by the British Government Fuel Research Board in 1919-20 for its experiments on the practice of steaming retorts and on low-temperature carbonization.

A view of the coal magazines and upper operating floor is shown in Figure 153. The coke extractor in this system is of a helical form, set vertically, being essentially a screw conveyor, for which the gears and general arrangement may be seen in Figure 149. In general principle the retort operation is similar to that already described.

The Steaming of Vertical Retorts. The continuous vertical retort is especially well adapted to the steaming process. This process, as applied therein, may be said to be now an established success, and where conditions do not require more than 530 B.t.u. in the gas per cubic foot, is a normal adjunct to the operating system.

The intermittent verticals, the horizontals, and the by-product coke oven have used the steaming process and found it in some degree advantageous. But their intermittent character restricts the application of steam to a limited period at the end of the carbonizing period when sufficient coke at the requisite temperature has been formed.

In the continuous vertical, steam can be superheated by the hot coke in the lower section of the retort, and then pass to the hotter coke above, with which, and with the carbon on the walls, it enters into the water gas reaction, the gases thus generated passing *through* the upper strata while carbonization is under way. These conditions are particularly favorable to improved quality in gas and increased ammonia yield. Reaction of the steam with the highly-heated carbon coating on the retort walls is a large factor in the total production of water gas by this process, and is advantageous in reducing materially the time of "scurfing" required.

The steaming of retorts is in effect a diluting of the gases of coal carbonization by blue water gas. It is more than that, however, since it provides also the desirable "sweeping" effect—and "mass" effect of hydrogen—to the nascent coal gases, promoting materially the yield of gas-form B.t.u.'s.

From the results of Blundell, Table 54, page 367, it is apparent that in his experiments an increase of 29 per cent. in gas yield was obtained with a decrease of but 4 per cent. in heating value, an increase, in fact, of 23 per cent. in the yield of gas-form B.t.u. per pound of coal.[4] This gain in the gas, however, is obtained at the expense of a considerable outlay for steam (larger per M of gas than required in a separate water gas generator), a loss in coke yield (but less than would be consumed in a separate generator), and the excess fuel required to heat the setting.

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[4] Subsequent investigations by others (including the Fuel Research Board) have shown that these figures of gain by steaming cannot be attained with all grades of coal, but probably express a conservative average.

To determine the value of steaming at any particular plant, the local requirements and conditions are to be correlated with the items of gain and expense, a number of which may be summarized as below:

TABLE 52.

SUMMARY OF THE GAIN AND LOSS IN STEAMING OF GAS RETORTS.

Items of Gain	*Items of Loss*
1. Increased make of B.t.u. in gas per pound of coal.	1. Cost of steam used.
2. Less carbon, and reduced scurfing time.	2. Cost of increased producer fuel.
3. Increase of ammonia.	3. Reduction in coke yield.
4. Increase of tar.	4. Lowered heat value of gas per cubic foot, and increased cost of distribution per unit of heat content.
5. Increase of hydrocarbons in gas and light oil per pound of coal.	5. A possible, but doubtful, deterioration of physical quality of the coke.
6. Lowering of capital, overhead and operating expense by increased output per retort per day.	

Tests by the British Fuel Research Board [5] on steaming in Glover-West vertical retorts have led to the conclusion that the process, up to a limit provisionally set at 20 per cent. of steam [6] is economically advantageous. With greater quantities of steam, it is likely not to repay the costs and balance the increasing disadvantages. By an expenditure of 10 "therms" (100,000 B.t.u. each) in the form of steam and fuel, there is said to be a gain of 33 therms in the gas yield, 34 pounds of tar and 6 pounds of ammonium sulphate, all per (gross) ton of coal.

Many plants of continuous vertical retorts in America are using moderate steaming with good gain in yields and economy. Plants so operated are at this time located chiefly in Connecticut, Massachusetts and New York State, where the B.t.u. requirement is approximately 530 B.t.u. per cubic foot (or in Canada where the requirement is still lower). The amount of steam used is ordinarily between 5 and 10 per cent.

Actual operating data of the Meriden, Conn., plant of 12 Woodall-Duckham 6-ton retorts, over a period of nine months, 1923, have been furnished the author,[7] and are reproduced in Table 53. Steaming was used on this plant continuously during the period. Flue temperatures in the settings ranged from 2,000° to 2,350° F.[8]

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[5] Dept. of Scientific and Industrial Research, Fuel Research Board, Report for 1920-21, Sect. 1, H. M. Sta. Office, London; also later results in Technical Paper 8, 1922.

[6] For certain kinds of coal the limit of steam is set at 10 per cent.

[7] By courtesy of Chas. A. Learned, General Manager, The Meriden Gas Light Co.

[8] Earlier results at the Meriden plant on steaming of the retorts are given in *Gas Age*, Jan. 10, 1921.

TABLE 53.

AVERAGE COAL GAS RESULTS—1923.

The Meriden Gas Light Co.
(Meriden, Conn.)

TWELVE 6-TON WOODALL-DUCKHAM VERTICAL OVENS.

	Make M. cu. ft. Corrected	Make Per Retort M. cu. ft. Corrected	Retorts on	Thruput Coal, Net Tons Per Retort	Fuel Per 100 Pounds Coal Carbonized	Yield cu. ft. Per Pound	B.t.u.	Thermal Feet	Producer Fuel Pounds
January	837	76.7	10.9	6.37	14.65	6.05	540	3,270	20,380
February	814	72.1	11.2	6.13	14.2	5.90	532	3,140	19,520
March *	780	70.0	11.15	5.84	14.8	6.00	533	3,198	19,346
April	822	74.3	11.06	5.88	14.8	6.32	538	3,400	19,305
May	807	71.8	11.25	5.80	14.2	6.18	533	3,294	18,500
June	781	70.5	11.1	5.55	13.7	6.34	528	3,348	16,798
July	783	70.5	11.1	5.57	13.9	6.34	539	3,420	17,176
August	760	68.4	11.1	5.35	13.9	6.41	538	3,448	16,500
September	773	69.6	11.1	5.45	14.8	6.40	539	3,443	17,918

* Coal from storage pile for half this month. Retorts steaming at rate of 30 pounds through $\frac{3}{16}$-inch orifice.

The data of J. E. Blundell, often quoted, on relative results with steaming and without, in Glover-West continuous verticals are given in summary, in Table 54.[9]

TABLE 54.

EXPERIMENTS ON "STEAMING" IN CONTINUOUSLY OPERATED VERTICAL RETORTS.

By J. E. Blundell.

(*London Gas Journal,* October 30, 1917.)

	Without Steam Average for 12 Months End Mar. 31, 1915	With Steam		Average Per Cent. Increase by Steaming
		Test on June 4, 1917	Test on Aug. 13, 1917	
Gas made per ton.....	12,049	15,500	15,477	29.2
B.t.u..................	530	510	508	—4.10
Analysis of gas:				
CO_2	2.4	3.0	2.0	4.0
C_nH_m	2.4	2.4	2.2	4.0
O_2	.0	.0	.0	.0
CO	9.8	10.6	13.6	23.5
CH_4	23.9	21.3	24.1	—5.0
H_2	53.2	54.4	49.65	—7.1
N_2..................	8.3	8.3	8.45	1.0
	100.00	100.00	100.00	
Total incombustibles ..	10.7	11.3	10.45	1.9

2 per cent. air added for revivification in situ.

		Average for 3 Months (End Aug. 31, 1917)	
Coke, per cent. of coal.........	68.0	67.0	—1.5
NH_3, pounds per ton...........	5.44	7.10	29.3
Tar, gallons per ton.............	10.9	16.61	52.4

The temperatures used at various levels in the tier of combustion chambers, with and without steaming were as follows:

	Without Steaming ° F.	With Steaming ° F.
Combustion chamber No. 1 (bottom).............	2,192	2,462
" " " 2	2,246	2,552
" " " 3	2,282	2,552
" " " 4	2,318	2,552
" " " 5	2,210	2,516
" " " 6 (top)	2,012	2,372

Yields of Gas and By-Products in Continuous Vertical Retorts. The yields of products from continuous verticals, without steaming of the charge, are not widely different from those obtained in the intermittent retorts and by-product coke ovens. The quantity of tar and light oil obtained is usually somewhat greater and the quality different, as previously stated (pp. 323 and 334-5). The following may be taken as average yields from high-grade gas coals, without steaming, under heating conditions prevailing in modern American practice:

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[9] *Gas Journal* (London), 140, 213-20 (1917); *Gas World,* 67, 322-7.

Gas—cubic feet per ton	11,500
B.t.u. in gas per pound of coal	3,300
Tar, gallons per ton	13.5
Light oil (included above in gas) gallons per ton	4.0
Ammonia, pounds NH_3 per ton	5.5

Ammonia yields higher than the above are frequently claimed as possible with vertical retorts, but a large number of actual yields in practice (in America) have come to the author's attention which average somewhat lower than that stated.

Processes of Complete Gasification

In the system known as "complete gasification," for which many processes have been proposed and several are under commercial trial, the coal is converted entirely into gas essentially by the water-gas or producer-gas process, combined with a certain amount of low-temperature carbonization of the raw coal. The latter is induced by the sensible heat of the water gas or producer gas passing directly through the raw coal, and by the heat of the "blow" gases and combustion thereof in flues surrounding the coal.

Through the combining of these processes in one apparatus or setting, it is evident that a reduction of heat losses occurs. A gain therefore in over-all thermal efficiency should result, and a saving in costs of operation.

Important by-products, however, in this system, are reduced or lost, notably ammonia, coke and tar. Question can legitimately be raised, in the absence of dependable balance sheets of extended commercial trials, whether the gain in over-all gas-making thermal efficiency by the proposed process may not be counter-balanced by the gains in by-products secured in a well ordered two-stage process using coke ovens or steamed verticals coupled with efficient separate water gas generators.

The complete gasification processes thus far proposed make a gas of low heating-value. It varies from 350 to 390 B.t.u. per cubic foot and cannot therefore be used at present for public distribution in America without enrichment.

Theoretical Considerations. Very little carbonization can be induced in raw coal by the amount of sensible heat in water gas or producer gas formed from its own coke. The following data of relative heat capacities and requirements will make this clear: [10]

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[10] The data on water gas produced per ton of coal (through low-temperature coke), sensible heat in the water gas and blow gases, and "potential" heat of

TABLE 55.

Theoretical Heat Transfer from Sensible Heat of Water Gas to Raw Coal.

Sensible heat in water gas, on total heat supplied to generator		1.81 per cent.
Sensible heat in blow gases, on total heat supplied to generator		4.74
Potential heat in blow gases, on total heat supplied to generator		20.94
		27.49 per cent.
Water gas made from the coke resulting from 2,000 pounds coal (75 per cent.) (with no deduction for coke used to raise steam)		34,300 cubic feet
Heat (in coke and steam) supplied to generator (based on 2,000 pounds coal)		18,000,000 B.t.u.
Sensible heat in water gas, based on 2,000 pounds coal (.0181 × 18,000,000)		326,000 B.t.u.
Sensible heat in water gas, based on 1 pound coal		163 B.t.u.
Heat required to raise 1 pound raw coal to carbonization point (750° F.):		
Latent and sensible heat, of water formed	62	
Latent and sensible heat, other vapors and gases	(?)	
Sensible heat of semi-coke (.75 × .36 × 700)	189	
Minimum total required for 1 pound coal		251 B.t.u.
Sensible heat required in water gas (if unassisted) to heat 1 pound coal to 750° F., assuming 50 per cent. efficiency in transfer		502 B.t.u.

It is evident that the sensible heat in water gas, after subtracting the amount required for evaporation and heating of water from the raw coal, is hardly sufficient (at 50 per cent. efficiency) to raise the temperature of the coal by 150 degrees F.

In the case of producer gas, whose production process has a greater degree of exothermicity, more sensible heat per pound of coal carbonized will be carried in the gas than is carried by water gas. But it is not likely to exceed 3 times the amount (unless increased by excess of combustion), and would still, unless transferred at a higher efficiency than commonly practicable, fall short of a suitable carbonizing heat for the equivalent coal from which it is derived.

Accordingly the "complete gasification" processes must depend, for their carbonizing heat, largely on the "blow" gases surrounding the upper chamber, or in producer-gas processes on an intensified combustion in the body of the producer. The blow-gases, as may be noted in Table 55, have relatively a large heating power, and if afforded opportunity for efficient application, could bring about a considerable measure of carbonization.

It is, however, impracticable to pass the blow gases *through* the coal

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the latter, are taken from similar data used by F. D. Marshall in presenting the theory of the Marshall-Easton process of "Low Temperature Carbonization by the Medium of Water Gas," in *Gas Journal* (London), **142**, 667-72 (1923).

and on into the final make of gas, owing to their high content of non-combustibles. When they are passed through checquers and burned *around* the raw coal chamber, their heat does not readily penetrate, with any practical speed, more than a few inches into the coal. Complete gasification processes, involving the water gas process, provide, in most cases, a superimposed raw coal chamber or shaft, too large in diameter to be heated throughout in this manner.

As a result of these difficulties, the principal drawback to complete gasification processes, in their prevailing design, makes its appearance. This is the fact of irregular and inadequate carbonization of the raw coal before it reaches the hot zones of partial combustion. In other words, much of the material capable of yielding hydrocarbons and valuable oils, passes through to be gasified, or attenuated, so to speak, by the action of air and steam.

Penetration of the hot producer gas or water gas uniformly into the coal is hindered by the softening of the coal (see Chapter 5, page 91) into a plastic zone or ring receding inward from the heated walls. Agitation of the mass is resorted to in certain low temperature carbonizing processes to lessen this difficulty.

Summary of Various Proposed Complete Gasification Processes.

For two reasons, a detailed account of complete gasification processes is omitted from this work. First, the proposed methods, so far developed, involve (as explained in preceding paragraphs) very little of coal carbonization, and are mainly modified water-gas or producer gas processes. Second, these processes are in an experimental stage, and do not as yet offer evidence of their practicability in the shape of records of extended runs, with detail of costs and efficiencies.

The following brief outline of the principal processes under trial will serve to guide the reader to a preliminary understanding.

Strache's "Double-Gas" Process. In Germany, H. Strache[11] developed, prior to 1916, his "double-gas" process, suggesting in principle most of the present-day proposed complete gasification processes. Figures 154 and 155 indicate the steps of the process and the type of apparatus, diagrammatically. First, air is blown through the generator, the central section, from right to left (Figure 154), saving the waste heat in a boiler; then water gas is made by passing steam as in Figure 155, the "make" gases issuing through the column of raw coal above, transmitting their sensible heat thereto. Additional heat to effect carbonization is secured by admitting a limited amount of air in the upper part of the generator during the "make." Another "blow" follows, reversing the direction, and passing this time from left to right.

[11] *Zeit. für angewandte Chem.*, 30, 106 (1917); *Jour. für Gas-beleuchtung,* 63, 230-35 (1920); *Jour. Soc. Chem. Ind.*, 39, 477 A (1920); also, *Gas Age-Record,* 53, 129 (1924).

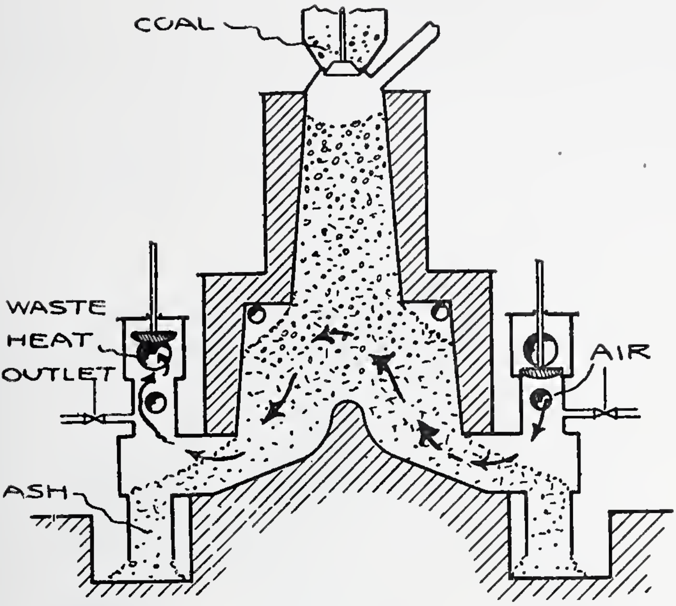

Fig. 154.—Diagram Illustrating Strache's Double-Gas Process, during Blow Period. (Courtesy of the American Gas Association.)

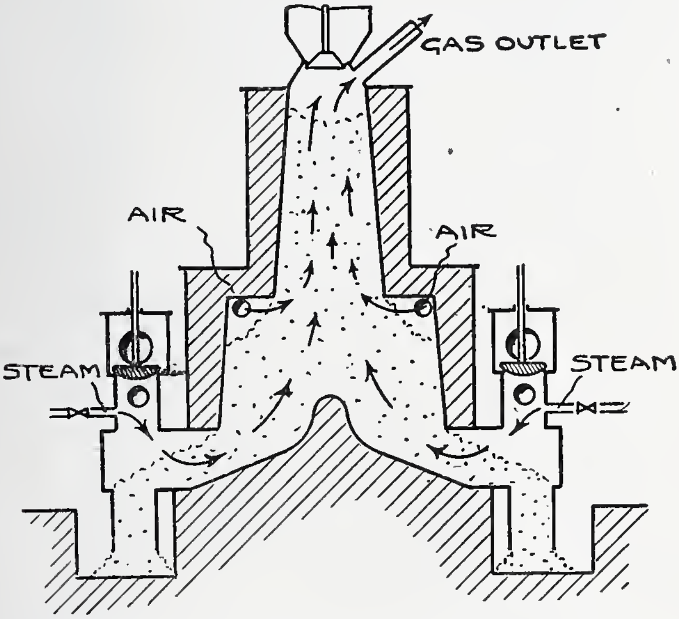

Fig. 155.—Diagram Illustrating Strache's Double-Gas Process, during Make Period. (Courtesy of American Gas Association.)

Yields are claimed equivalent to 51,000 cubic feet of 375 B.t.u. gas, per net ton of coal, without deducting fuel used for blowing and steaming the runs.

The "K. and A." and Related Systems. By the work of H. E. Smith in England and the development of the Kramer and Aarts sys-

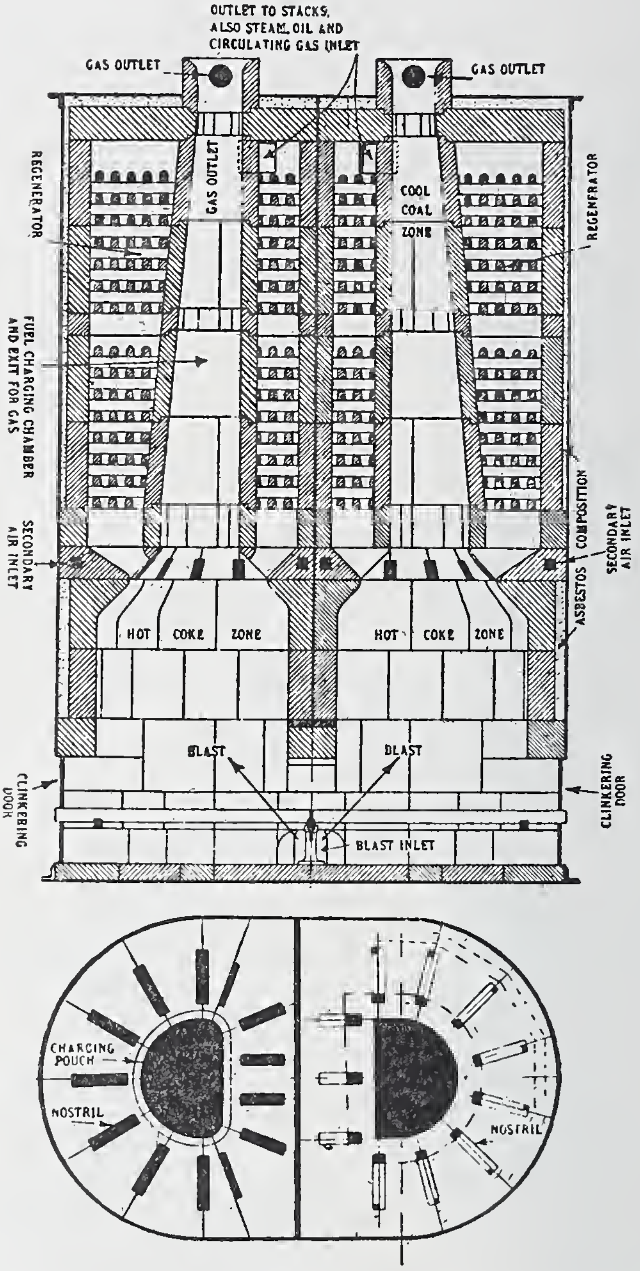

Fig. 156.—The Kramer and Aarts Double Gas System, as modified by H. E. Smith (vertical cross section above, horizontal section below).

tem,[12] similar principles to those of Strache were embodied in the double-column apparatus illustrated in Figure 156. Checquer-brick chambers, or regenerators, surround the upper columns or retorts, of D-shaped section, and serve to retain the heat of the blow gases. After the blow period, steam is admitted at the top of one of the regenerators, say on the right, and blown downward through both of the lower fuel beds in series, the gas then issuing upwards through the retort on the left, where it heats the raw coal. After the next "blow," steam is passed in the opposite direction.

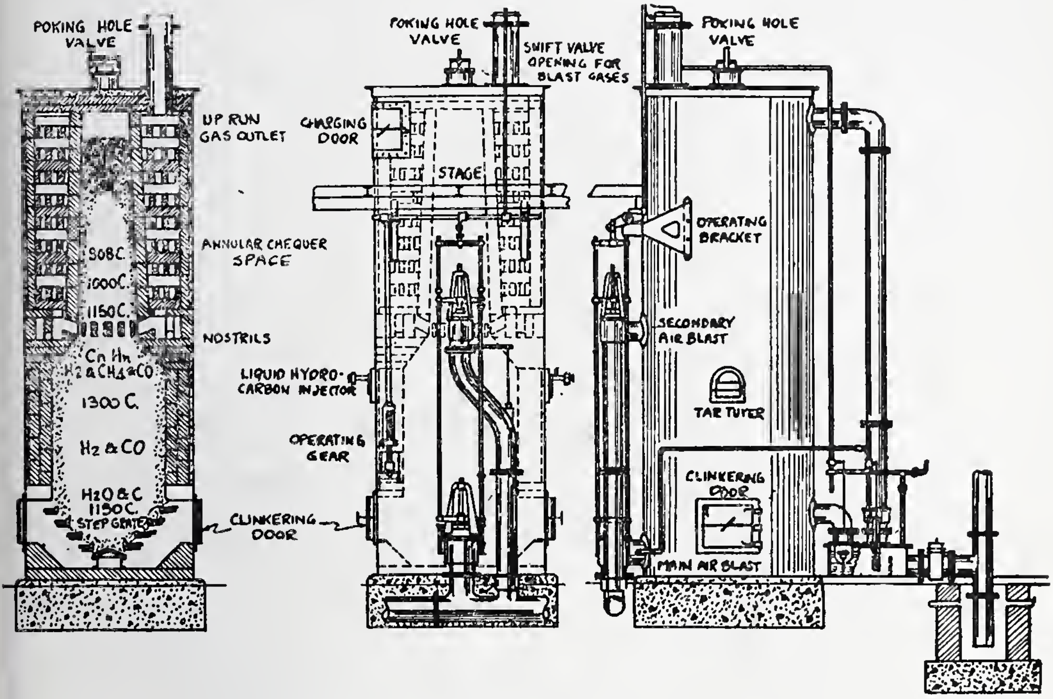

FIG. 157.—Tully's Gas Plant (for Complete Gasification). (Courtesy of American Gas Association.)

The Rincker-Wolter "Remainderless" Process, operated at Utrecht, Holland,[13] is of similar type to the "K. and A.," but with certain special features. Based on results of a 3-months run, yields are claimed which show a thermal efficiency of 57.5 per cent., capable of being raised to 68.5 per cent. by the use of waste heat boilers.

The Tully Process. In a number of small plants in England, where flexibility and simplicity is a requirement, the Tully process,[14] referred to as a "one-man plant," has found application. This process is illustrated in Figure 157. The principles of its operation are similar to those of the K. and A. system. After a blow period heating the checkers, a make period upward through the retort, and another blow period, the next make is downward through the checkers and producer.

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[12] *Gas Age,* 1921, p. 129; Alwyne Meade, "Modern Gas Works Practice," J. Allan & Co., London, 1916, pp. 478-82, for detailed account of this and other processes of complete gasification.

[13] *Gas Age-Record,* **48**, 205 (1921).

[14] *Gas Journal* (London), Dec. 22, 1920; May 11 and Oct. 26, 1921; Jan. 11, Feb. 8, and June 14, 1922.

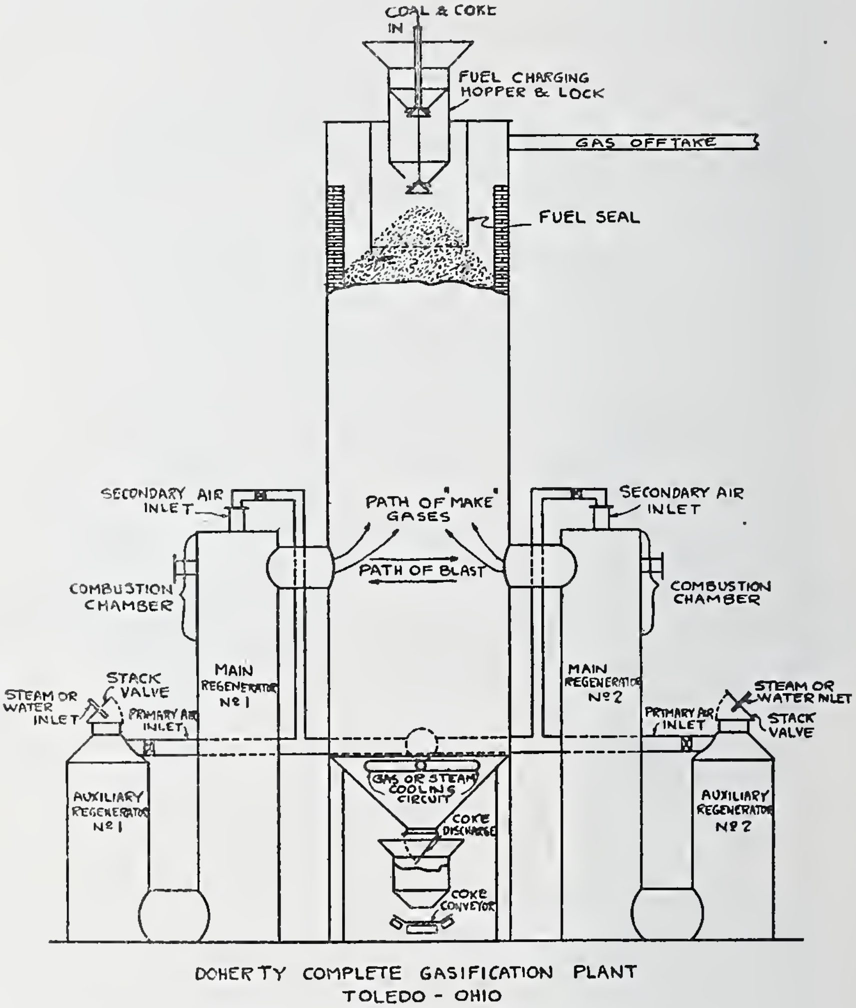

FIG. 158.—Diagram of Doherty Complete Gasification Plant. (Courtesy of American Gas Association.)

By suitable variation in the length of these periods and by optional introduction of enriching oils at the top of the generator during the make periods, the gas yield and quality can be varied. Coke is sometimes mixed with the charge to facilitate its passage downward in the retort and generator.

Tully plants have claimed efficiencies of 70 per cent. or slightly higher, including the yield of 8 or 9 gallons of tar, and not deducting fuel requirements, but these claims, owing to difficulties of practical measurement, are not to be considered as fully substantiated.

Doherty's Complete Gasification Process.[15] As operated experimentally in a plant of commercial size at Toledo, Ohio, this process is illustrated in Figure 158. It applies similar principles to those already described, but has no checker brick chambers surrounding the carbonizing retort. Separate outside regenerators of ample capacity are provided, to recover waste heat and return it to the system, but direct transfer of sensible heat of the "make" gas is relied upon entirely to preheat and carbonize the raw fuel.

Other complete gasification processes, to which reference can be made here only by name, are listed below:

W. D. Wilcox Process: U. S. Pat. No. 1,372,731 (March 29, 1921), and No. 1,386,825; Gas Journal (London), June 8, 1921, page 553; Gas Record, 18 (1920), pages 11-14; Gas Age-Record, 52 (1923), 705-707.

E. F. Murray Process (British): Gas Journal (London), October 18, 1922, page 175; and November 15, 1922, page 435.

Tenney Process, promoted by the American Gas Construction Co., Newton, Iowa.

Whitwell-Young Process (of water-gas manufacture), called the "back-run process," U. S. Pat. No. 1,468,190, September 18, 1923, and which uses bituminous coal as a generator fuel in such manner as to constitute essentially a complete gasification process. This process has been in successful commercial operation, at the time of this writing, for more than one year. It is described in Chemical & Metallurgical Engineering, 29 (1923), 664-9.

Gas Making by the Aid of Oxygen

In June, 1920, H. J. Hodsman and J. W. Cobb gave to the British Institution of Gas Engineers[16] probably the first clear presentation of this subject in their paper on "Oxygen in Gas Production." Since that time the subject has been actively discussed in America as well as in England, and its interest and promise given due acknowledgment.[17]

As yet, however, so far as is known to the author, neither experimental work on a large scale nor commercial operations using such a process have been undertaken, partly no doubt owing to the fact that a sufficient supply of cheap oxygen has not been available.[18]

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[15] H. L. Doherty, U. S. Pat. No. 1,426,159 (Aug. 15, 1922).

[16] *Gas Journal,* June 8, 1920, 640-7.

[17] E. A. W. Jefferies, "Gas Making with Cheap Oxygen" (paper presented to New England Association of Gas Engineers, February, 1921); L. J. Willien, "Complete Gasification of Coal by the Use of Oxygen," *Amer. Gas Assoc. Monthly,* 1923, 565-70 (September).

[18] Private communication to the author, December 4, 1923, from the Jefferies-Norton Corporation of Worcester, Mass., reported that work had been initiated

For straight carbonization of coal the use of oxygen is not of material aid. Discussion of the matter here accordingly leads somewhat afield. It is in aid of coal gasification, i.e., producer gas, or water gas manufacture, and particularly in improvement of the so-called "complete gasification" process, that the use of oxygen holds out great promise, carbonization appearing herein only as an incident to the procedure.

Woodall, Duckham and Jones, in Brit. Pat. 185,461 (May 3, 1921) and U. S. Pat. 1,447,839 (March 6, 1923) propose the treating of coal, in a vertical retort alternately with steam and oxygenated air (in which nitrogen is contained in amount less than 40 per cent. of the volume of oxygen), the waste heat being utilized in the setting and in boilers.

When coal is gasified by air and steam, in thermally proportioned quantities, as in modern producer practice, the nitrogen of the air appears as a diluent, carrying sensible heat away, lowering the heating value of the gas produced, and making its distribution costly. If, by the use of oxygen, the gas producer method can become feasible for the manufacture of a public utility gas, in high yields, of a practical B.t.u. value per cubic foot, the justification of a new cost item in the shape of oxygen is easily found, and the item in fact is balanced, in all probability, by the saving in capital and operating costs per therm of gas. For American conditions some enrichment of the gas would be required.

On comparing theoretically the thermal efficiency of gasification by use of oxygen, to that of best modern producer gas practice, large sources of gain therein are not readily apparent. But when compared to any of the existing processes whereby a *high-grade* gas, say of 400 B.t.u. or better, is produced, the oxygen method has a large advantage in over-all efficiency, owing to its ability to use the "blow" period for gas making, instead of discarding this gas, or utilizing only its heat of combustion.

The use of oxygen does not afford any great opportunity for gain in connection with the formation of hydrocarbons by carbonization in the upper layers of the producer charge, nor in recovery of sensible heat from the gas.

In fact there is some possibility of increased difficulties and losses of efficiency, as Hodsman and Cobb have pointed out (*loc. cit.*) in local overheating and attack on the furnace linings, uneven progress of the gas reactions, etc. But good prospect appears that dangers from such difficulties may be held low.

Gains by use of oxygen are to be looked for chiefly in factors and conditions consequent to the increased heating value of the gas (as compared to ordinary producer gas) and in the simplified process of manufacture. The cleaning, handling and delivery of the gas becomes

on the installation at Worcester, of a gas-making plant to use oxygen, of a capacity between 600,000 and 900,000 cubic feet of gas per day.

less costly, due to its greater concentration, and the expense of providing the blast to the producer is materially reduced.

Oxygen, on a large industrial scale, can be manufactured, according to E. A. W. Jefferies[19] at a cost varying from 10.1 to 15.1 cents per 1000 cubic feet, including capital and other fixed charges, as the operation varies from 3 million to 2 million cubic feet per day. This estimate is on the basis of the air distillation process developed by the Jefferies-Norton Corporation. The same authority estimates a requirement of 200 cubic feet of oxygen per 1000 cubic feet of 375 B.t.u. producer gas made, which is equivalent, on the basis of the gas made, to 2 to 3 cents per 1000.[20]

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[19] *Loc. cit.,* see Note 17.

[20] See also, on this subject, Report of Investigations, No. 2502, Bureau of Mines, July, 1923, by F. W. Davis and Committee, on "The Use of Oxygen or Oxygenated Air in Metallurgical and Allied Processes," whose estimate of the probable cost of oxygen in "large quantities" for industrial purposes is $3.00 per gross ton (or about 11.4 cents per 1,000 cubic feet).

Chapter 13.

Low Temperature Carbonization Processes.

General. The subject of low temperature carbonization, in its economic phases, has been given attention in Chapter 3 (pp. 65-7). The gas and oils produced have been described in Chapter 11 (pp. 313, 322). It remains to sketch briefly some of the processes which have been proposed and tried.

These processes are, none of them, as yet proven in a commercial sense, i.e., so as to show their ability to carbonize coal at costs well within the revenue to be derived from the products.

Difficulties to be Overcome. The reason-for-being that is most rationally assigned to carbonizing coal at low temperatures, is its theoretical ability to produce a higher yield of the aggregate of values in the products. There is less degradation of primary oils and gases from the coal into carbon and low-value heavy hydrocarbons, less loss therefore in available values. Such a system should make for efficiency and conservation.

But two disturbing elements arise to counteract this gain in thermal and material efficiency, (1) technical difficulties in operation, chiefly concerned with transmission of heat to the coal at a reasonably rapid rate, and (2) difficulty in establishing favorable commercial values for the new and somewhat unusual products.

The first-named difficulty, viz., to reach, in operation, a reasonably practical rate, is a serious one, in that plant capacity, plant cost and labor cost per ton of output, and indeed the question of commercial success or failure, depend in great measure upon it. Efforts to solve the problem and provide for a reasonable rate of heat transmission to the coal, at the low heat-head available, are to be seen in the outline of the various processes given below.

The marketing difficulty can no doubt be overcome in time. The oils, merely for their fuel value, secure at least 75 per cent. greater return than the tar from high temperature processes. The coke, when well made, can secure, in markets outside of the metallurgical field, 10 per cent. greater return than high temperature coke. Light oils, in some instances, may yield a gain. These gains, through the values of oils and coke, are offset in a large degree by the loss of gas value, and the system therefore has but a small margin to fall back upon for meeting added plant and operating costs.

Technical Requirements. To secure success in any low temperature process of coal carbonization, there is required either a method of heating the coal in thin layers or of turning or agitating the charge so as to heat all sections of it with a reasonable rapidity. Another requirement, in an agitation process, is a mechanical design such as will move the mass of plastic, sticky material without injury to the parts or loss of products. Carbon and coke tend to build up on the retort and moving parts, clogging the mechanism and the movement of the coal.

When operation is irregular, by reason of shut-downs for repairs, and delays for cleaning out, "scurfing," or the like, costs mount rapidly, both overhead and current. Such difficulties have in many cases stood in the way of commercial operating success with the processes thus far developed.

For a discussion in detail of the technical and economic problems involved in low temperature coal carbonization, written from the British viewpoint, but in great measure applicable generally, the reader is referred to the Second Section of the Report of the British Fuel Research Board for 1920-21, Low Temperature Carbonization (published by H. M. Stationery Office, London, 1922).

Outline of Various Processes.

The processes proposed for low-temperature carbonization may be grouped or classified in various ways. Perhaps the principal point of distinction lies in the fact of being continuous or intermittent with stationary charge. The following grouping is therefore suggested:

TABLE 56.

LIST OF LOW TEMPERATURE CARBONIZATION PROCESSES.

A. Stationary-Charge Processes:
    1. Parr
    2. Tozer (of the Tarless Fuel Co., British)
    3. "Coalite" (British)
    4. Wallace

B. Continuous Processes:
  (a) Internally heated, by passage of hot gas:
    5. Nielson (British)
    6. Marshall-Easton (British)
    7. McLaurin producer (British)
    8. Bussey producer

(b) Externally heated:
  9. Traer oven
  10. Richards oven (British)
  11. Piron-Caracristi lead-bath oven
  12. Del Monte
  13. Greene-Laucks
  14. "Carbo-coal"
  15. Pritchard-Whitaker

Description of the Processes.

Illustrations of apparatus accompany the description of those processes to which the greatest industrial promise appears to be accorded, and reference wherever possible is made to detailed descriptive articles in the literature. Much of the material set down under this heading is abstracted from such articles. The author acknowledges indebtedness to reports on Low Temperature Carbonization made to the American Gas Association by C. V. McIntyre, J. D. Davis, and H. A. Curtis,[1] some of whose reviews and abstracts are quoted here in full.

Stationary-Charge Processes

Parr's Process. Detailed description of Parr's apparatus (developed by S. W. Parr and associates at the University of Illinois), is not yet available in published form. The principles of the method and an outline of the earlier form of apparatus appear in the literature.[2] Experimental work is still actively under way, and at the time of this writing (1923), information[3] is at hand that erection of a large experimental unit of commercial size is being initiated.

The process involves two steps, (1) preliminary heating of the coal to a point short of fusion in a revolving drum, or other means providing agitation, (2) final coking in a vertical shaft retort of narrow cross section heated externally to 1100°-1300° F. The essential principle involved, as claimed by the inventor, is the utilization, in this second step, of internal autogenic heating, as an auxiliary, induced by the exothermic reactions occurring in certain stages of the carbonization of high-oxygen coals.

The process has been operated, in preliminary trials, by the intermittent method, but may be adapted to continuous operation in manner similar to that of the standard vertical gas retort systems.

The Tozer Process (Tarless Fuel Co., Battersea, England). This process was one of the earlier English developments and reports of its recent progress are meager.[4] The following description, based on articles by F. D. Marshall[5] is quoted from an American Gas Association report:

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[1] Techn. Sect. Sessions, Amer. Gas Assoc., 1920, pp. 105-138; Report of Carbonization Committee, Amer. Gas. Assoc., 1922; *ibid.*, 1923.

[2] Bull. 79, Univ. of Illinois, Eng. Expt. Sta., 1915; *Jour. Ind. Eng. Chem.*, 13, 14-17 (1921).

[3] Private communication to the author, from S. W. Parr.

"The Tozer retort is built entirely of cast iron, and consists of two thin, concentric, annular carbonizing chambers, provided with ribs, for the better conduction of heat to the charge. These ribs run from top to bottom of the vertical retort and divide the charges in both the inner and outer annuli into four sections. Both chambers are slightly thicker at the bottom than at the top to facilitate discharging, and half of the vapors formed escape upward through the charge to the collecting drum at the retort top and the other half downward through the charge, then upward through the gas duct in the retort center. Doors of special gas-tight design are fitted to the top and bottom of the retort, and the bottom or discharging door is balanced by counterweights for easy action. The retort charge is about one-fourth of a ton. There are six units in a bench, and each unit is completely walled in with fire-brick so that flames do not impinge directly on the iron.

The heating is started with producer gas, and as soon as the carbonization is well under way, the producer gas is turned off and the carbonization is finished with gas from the charge. Some of the retort gas is also used for power and there is still an excess. Gas yield figures are not given. The carbonization time is 4½ hours. The capacity of the Battersea retort bench (six retorts) is about 2,200 pounds per charge, and the plant will, therefore, handle about 50 tons of coal per week. A vacuum of 27 inches mercury is maintained on the retorts during carbonization."

The "Coalite" Process (Low-Temperature Carbonization, Ltd., London). The "Coalite" process, in its earlier career (following the year 1902), was extensively advertised in England, and served to draw wide attention to low temperature coal carbonization at that time. The early type of retort, not commercially successful, has been superseded by an oven having an unusual attachment for facilitating heat transfer and the discharge of the coke, consisting of a pair of collapsible iron plates, within the oven, between which and the walls the coal is held in a thin layer, and which permit its discharge vertically when coked.

The following description[6] gives the essentials of the process.

"The most successful retort of the coke oven type developed so far is that of the 'Coalite Process' used by Low Temperature Carbonization, Limited, in their Barugh Plant, near Barnsley, England. This oven is 11 inches wide, but there are collapsible iron plates in the center of the oven and the width of the coal sheet is actually only about 3½ inches. The oven wall is of fire brick and is 3 inches thick. The flues run horizontally along the oven walls, the waste gases passing through recuperative systems at ends of the oven. The coking time claimed by the company is eight hours and this appears reasonable. No data are available as to what flue temperatures are carried, but it is not likely that they are much below 900° C. (1652° F.). The company has at times claimed a large percentage of excess gas for their process, but it is probable that the excess over that required for the ovens is not large.

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[4] Brief description of later form, *Chem. and Met. Engineering*, **30**, 471 (1924).

[5] *Gas Journal* (London), **145**, 383 and 451 (1919).

[6] By H. A. Curtis in Amer. Gas Association's Report of Carbonization Committee (1922). Description of Barugh plant (England), *Engineering*, **112**, 596 (1921); *Chemical and Metallurgical Engineering*, **26**, 23-28 (1922), **29**, 233-38 (1923).

"All such processes, which involve the carbonization of coal in thin layers at low temperatures, suffer from the inherent difficulty of low capacity per retort. In the Coalite process, the capacity of the retort is about 1200 pounds per charge. On an eight-hour coking period, this would amount to 1.8 tons per day. A plant of 1000 tons daily capacity, which is about the minimum for conditions in the United States, would require 612 retorts, allowing for no spares."

Wallace's Process. The process invented by G. W. Wallace (Canadian Pat. 189,426) has been embodied in a semi-commercial installation at Petersburg, Va. (1921). The principles involved are presented in a recent paper on "A Study of Some Physical Laws Governing the Carbonization of Coal" by A. W. Warner.[7]

Vertical retorts are used, having in the center of each a hollow, perforated, metal core through which the primary gases and vapors of carbonization are drawn. Part of the leaner, secondary gases is drawn through the coke to an outlet in the top of the retort. Relative directional flow of the volatile products in this manner can be controlled by the amount of suction applied.

Wall temperatures higher than those customary in low temperature carbonization are used, so that a coke of a high degree of strength is said to be produced, with by-products similar to those of low temperature carbonization.

Internally Heated Continuous Processes.

The MacLaurin Producer. An early type of the internally-heated carbonizing chamber, utilizing the sensible heat of producer gas made in the same setting, the MacLaurin Producer, is described by C. V. McIntyre in the 1922 American Gas Association Report (*loc. cit.*) as follows:

"One of the first large scale developments for carbonizing coal and shales by passing producer gas through the charge was undertaken by Robert MacLaurin of Glasgow, and his experiments are said to have met with a certain degree of success, although no large commercial plants have been built.

"One type of retort, built during the course of experiments, consists of a vertical stack, circular in cross section and similar in vertical section to an hour glass with the contracted throat located about one-fourth of the height from the top. The lower section below the throat is built of steel lined with fire brick; the upper end is of steel and provision is made to circulate gases around it to aid distillation. Coal admitted through a valve at the top fills the retort and while traveling slowly downward is carbonized by heat carried by hot producer gas ascending through it. The producer gas is generated in adjoining apparatus. Coke is removed from the bottom by mechanical means.

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[7] *American Gas Association Monthly,* July, 1923.

"In another type of apparatus built by MacLaurin the producer and the carbonizer are combined in one apparatus and operated in such manner that a portion of the coke is gasified, the remainder being removed by a mechanical device and quenched.

"It is said that MacLaurin has succeeded in operating his retort or kiln with a caking coal screened to lump size without encountering trouble from the coal sticking or melting, and that, in fact, the carbonized residue is of the same size and shape as the original lumps. The absence of intumescing is attributed to the slow application of heat. Whatever the explanation, the result is interesting, particularly to those experimenters who have experienced difficulty with a pasty mess of melted coal in their retorts."

Reports of developments with this process, indicating its recent progress, are not at hand.

The Bussey Producer. Applying a method very similar in principle to that of MacLaurin, C. C. Bussey,[8] in America, patented his simple form of single shaft producer, operating continuously by means of a coke extracting grate at the bottom. He made therewith a number of trials, in various localities, and on a variety of coals, but none of these has as yet led to commercial operation.

A semi-commercial unit of this process, developed and modified in structural detail by other engineers, has been operated for test purposes recently at Louisville, Kentucky, on a scale of 24 tons of coal per day. The yields of oil obtained are said to be remarkably high, and the coke, in these later tests, to be dense and strong. Thermal balance sheets and operating results have not been published.

The distinguishing feature of the process appears to be continuous mechanical discharge of the coke prior to its complete combustion or gasification, the heat of the partial combustion being transmitted by the ascending gases to the upper layers of the charge for securing a certain measure of carbonization thereof.

Difficulties, more or less to be expected, were encountered with this apparatus (in its early form) from having the hot zone of a producer in contact with a discharging grate, and from the hanging-up and channelling of a carbonizing mass (unless non-coking) in a producer shaft not provided with agitating device, and whether these are capable of practical solution under the later modifications, remains to be demonstrated by the results of extended and continuous trial.

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[8] U. S. Pats. 1,191,869-870, July 18, 1916.

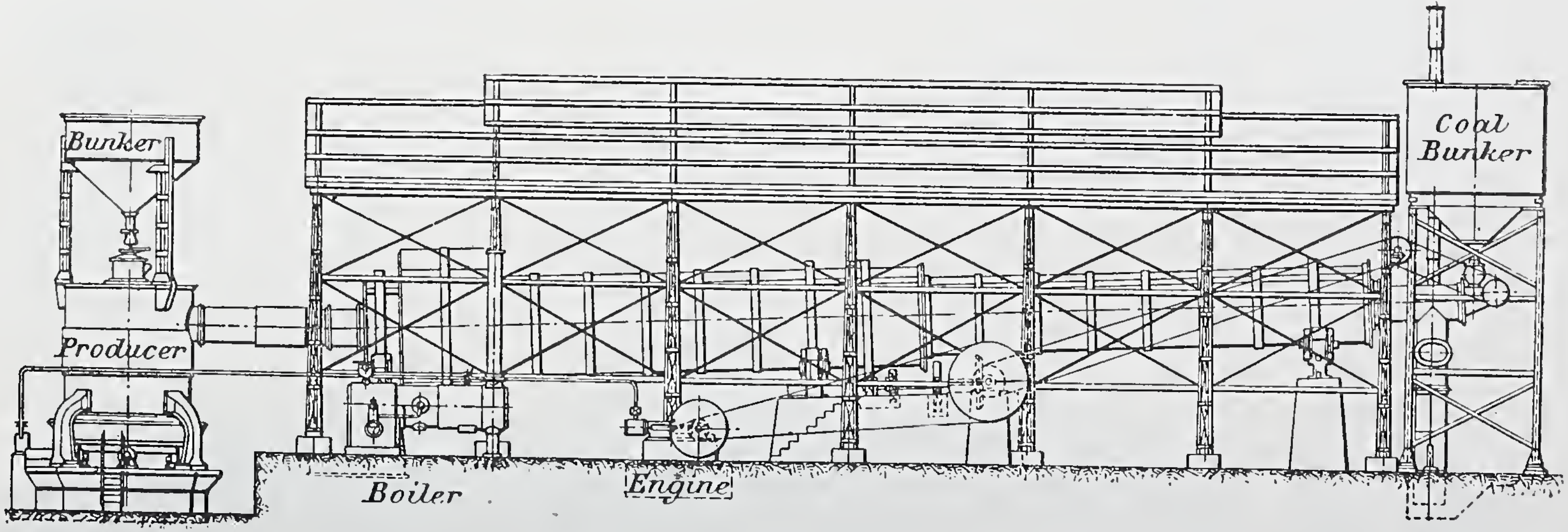

FIG. 159.—Nielson's. Revolving Retort for Low Temperature Coal Carbonization. (Courtesy of *Chemical and Metallurgical Engineering.*)

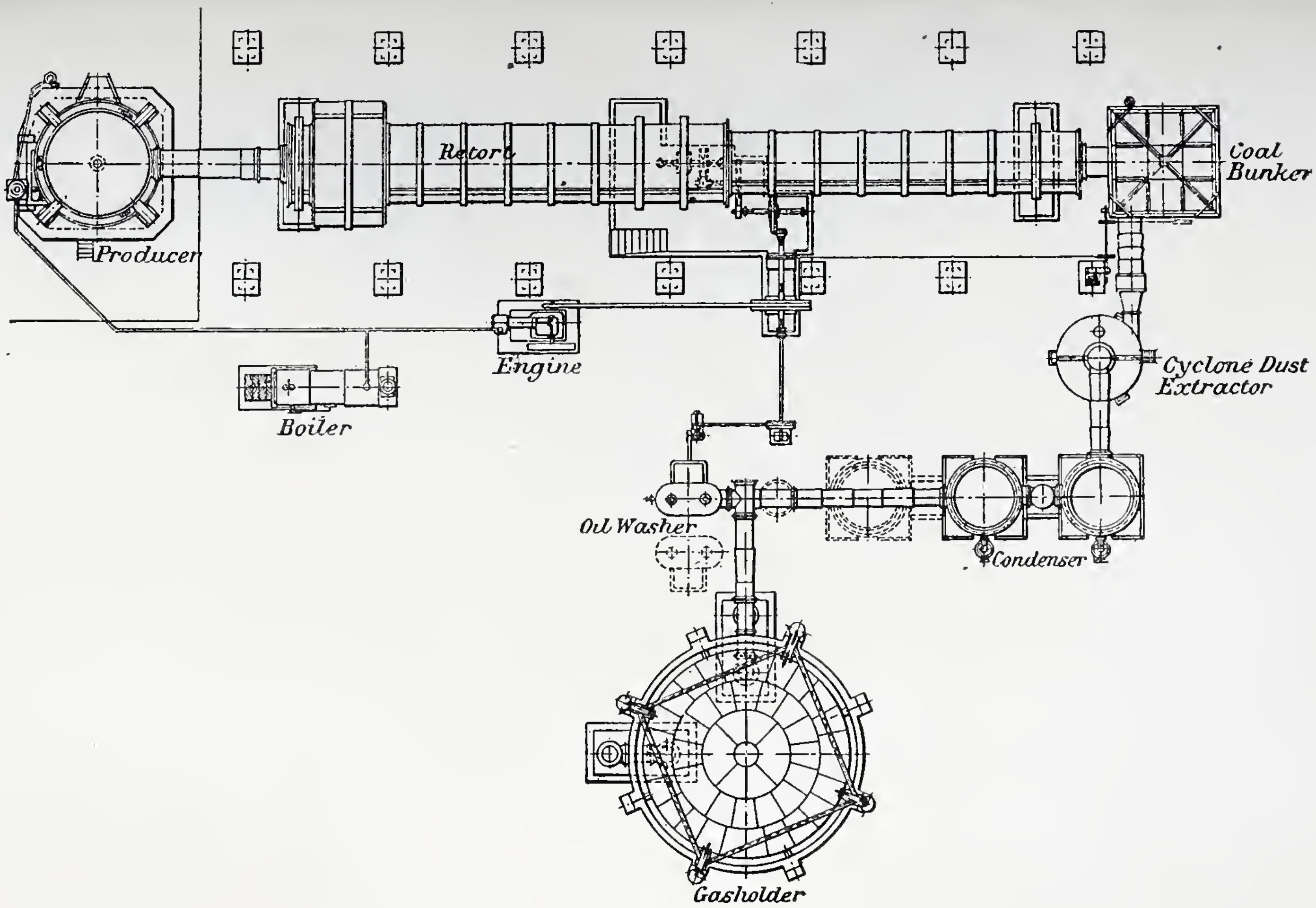

FIG. 160.—Nielson's Revolving Retort for Low Temperature Coal Carbonization, Plan View of Plant. (Courtesy of *Chemical and Metallurgical Engineering*.)

The Nielson Revolving Retort. A recent development in England of the use of the sensible heat of producer gas for carbonizing, is the revolving retort of H. Nielson.[9] The hot gas from a detached producer is fed into one end of a long cylindrical revolving retort, passing through a tumbling mass of coal which enters from the other end. Figures 159 and 160 show the general arrangement.

A plant is said to be operating with this process on a scale of 100 tons of coal carbonized per day. The retort is 90 feet long, 7 feet in diameter at the feed end and 9 feet at the discharge end, set on a slight angle with the feed end higher, and turning at 16 revolutions per hour. The coke discharges into an annular belt 14 feet in diameter around the lower end of the retort and is periodically emptied through hand-operated doors.

The coal requires 2½ hours to pass through the retort. Hot gas enters at 1380° F. and emerges at 240°-480° F. The producer uses 40-45 per cent. of the coke produced. Yields are claimed, per gross ton of coal, as follows:

Semi-coke (net)	8.5 cwt.
Gas (of 230 B.t.u.)	44,000 cubic feet
Oil	20.0 gallons
Ammonium sulphate	15.2 pounds

On the basis of these claims the heat value of the products, on a reasonable estimate, would aggregate 23,000,000 B.t.u. per gross ton of coal, indicating thus an over-all efficiency of nearly 90 per cent. The steam used in the producer is, however, not probably deducted here.

Inasmuch as the heat transfer from 39,000 cubic feet (the yield claimed per gross ton of coal) of producer gas at 1380° F., probably does not exceed 1,100,000 B.t.u. in cooling to 350° F. (heat capacity equivalent, 1060 pounds of water, times 1030 degrees temperature change), or 491 B.t.u. per pound of coal, and a minimum of 190 B.t.u. from this must be assigned to the evaporation of water, etc., and to radiation losses, the maximum available heat to effect carbonization is 300 B.t.u. per pound of coal. At the point of highest temperature, there would be produced, theoretically, by this, not more than 1000° F. in the solid carbonizing material, and probably less.

Published reports of operation of the process appear to show that a heat transfer approximating the above is secured and that the temperature of the coal reaches 800° F. or higher. Whether this temperature and the method of retorting used can produce a coke of saleable quality would seem to be an important question answerable only by extended commercial trial.

The Marshall-Easton Process. This is a continuous process utilizing both the sensible heat of water gas (passing through the coal) and the heat, sensible and "potential," of the blow gas (passing around the retort). It was developed recently in England by F. D. Marshall

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[9] *Chemical and Metallurgical Engineering,* 29, 1008-12 (1923).

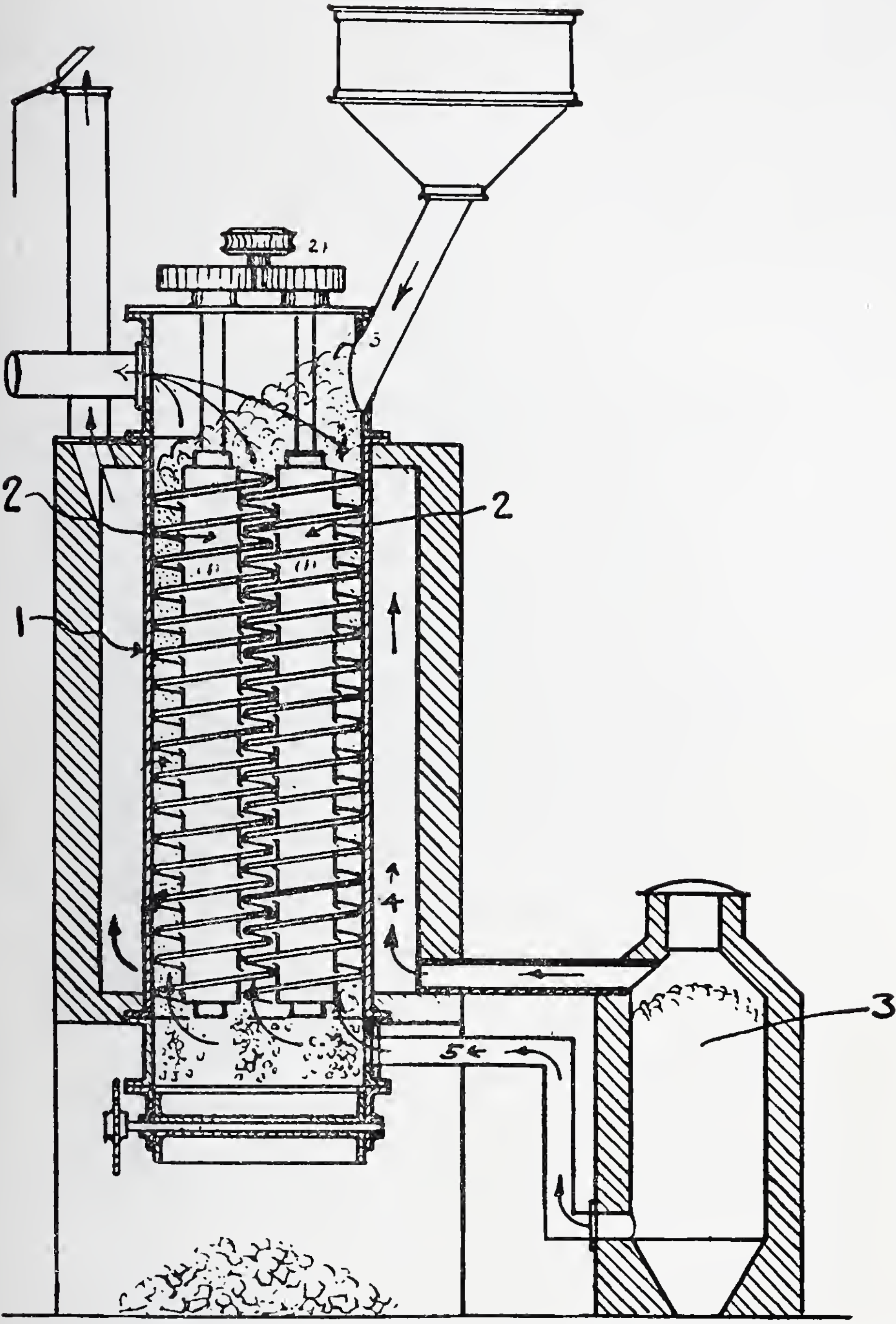

FIG. 161.—Marshall-Easton Combined Low-Temperature Carbonizing Retort and Water-Gas Generator. (Courtesy of American Gas Association.)

and R. W. Easton, the latter being the inventor of the over-lapping twin screw propeller.[10]

This process shows much promise, if mechanical difficulties in the movement of the propellers can be avoided, since opportunity is given for efficient heat transfer to a thin layer of coal (4½ inches) moving in a narrow iron retort surrounded by an ample source of heat in the blow gases from the generator.

It is illustrated in Figure 161. The following brief description (by C. V. McIntyre) is quoted from an American Gas Association report:

"The process may be termed a combination continuous retort and water gas generator, having an excellent thermal efficiency and producing a gas which may be varied between 376 and 502 B.t.u. without carburetting with oil. The retort, illustrated in Figure 161, consists of a cast iron shell (1), about 7 feet high, containing a pair of overlapping screws (2), each about 15 inches diameter with screw flights 4½ inches deep; means for driving the screws at a speed of about 8 revolutions per hour; a coal charging device at the top and a coke discharging gate at the bottom. The iron shell is mounted within a brick setting and heated by hot gases from a water gas generator (3), the "blow" gases (4) passing around the shell and heating it externally, while the "make" gases (5), pass directly through the retort and mix with the distillation gas. Thus the retort is heated both externally and internally. Coal at the rate of about 10 tons per day passes down through the retort on the screw flights. The inventor claims that the coal is not agitated or mixed by the turning motion, and that it is carbonized in about three hours, being discharged in two streams of coke, one from each screw. A portion of the coke is charged in the water gas machine, the amount being regulated so as to control the heat value of the mixed gas leaving the retort; the balance, or one-half to three-quarters of the total, is available for marketing."

The Richards and Pringle Process, of interest, as being an early effort to utilize the travelling pan conveyor idea, was developed in England, and a small trial plant built in America in 1921 at Hammond, Indiana. This plant was operated only a few months.

The Piron-Caracristi Process. Work has been begun on the installation of two comparatively large plants, utilizing this process, for the Ford Motor Co., at Walkerville, Ontario, and at River Rouge, Mich. An experimental installation, of one commercial unit, was in operation in 1922-23 at Huntington, W. Va.[11]

A travelling metallic belt or grate (Figures 162, 163 and 165) carrying a thin layer of coal, passes over the surface of a heated lead bath, all within a brick distillation chamber heated by gas-burning flues. Regenerators or recuperators are provided above the chamber to recover the heat of the waste gases. The conveyor plates carrying the coal, in a ½-inch layer, are heated to 1200° F.

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[10] Full description, with costs and operating data, published in article by F. D. Marshall in *Gas Journal* (London), 164 (1923), 667-72.

[11] *Coal Age,* 24 (1923), 171-73, description, by R. D. Lamie, of the experimental installation; *Power,* May 29, 1923, description, by V. Z. Caracristi, of the Ford Motor Co. installations.

Further details of the operation of this process[12] are given by C. V. McIntyre in the 1923 Report of the Carbonization Committee, American Gas Association, as follows:

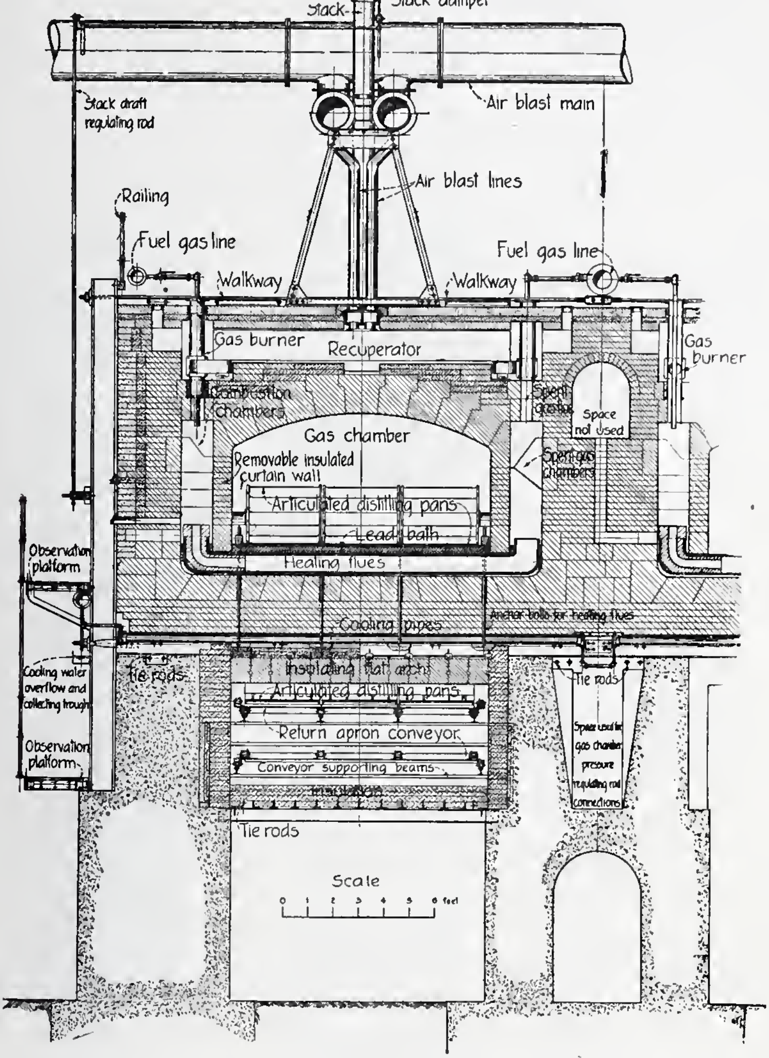

FIG. 162.—Piron-Caracristi Process of Low-Temperature Coal Carbonization, Transverse Section of Retort and Setting as built for the Ford Motor Company.

"The unit, designated by the inventor as one retort, consists of a brick setting containing two parallel retorts or ovens each 9 feet wide

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[12] The dimensions given do not apply to the late installations for the Ford Motor Co.

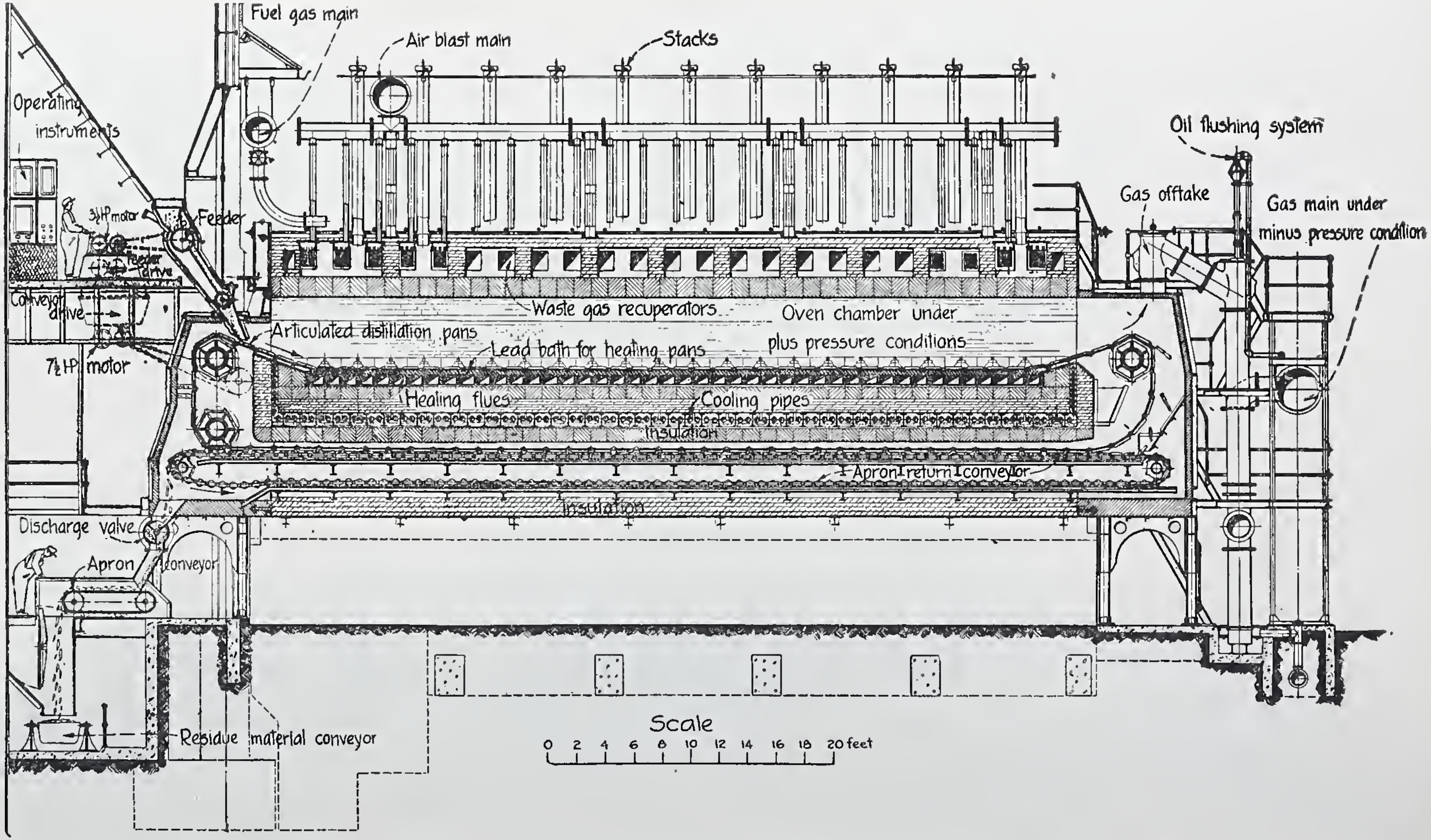

FIG. 163.—Piron-Caracristi Process of Low-Temperature Coal Carbonization, Longitudinal Section through the Oven and Setting as built for the Ford Motor Company (upper portion of coal bin on left not shown).

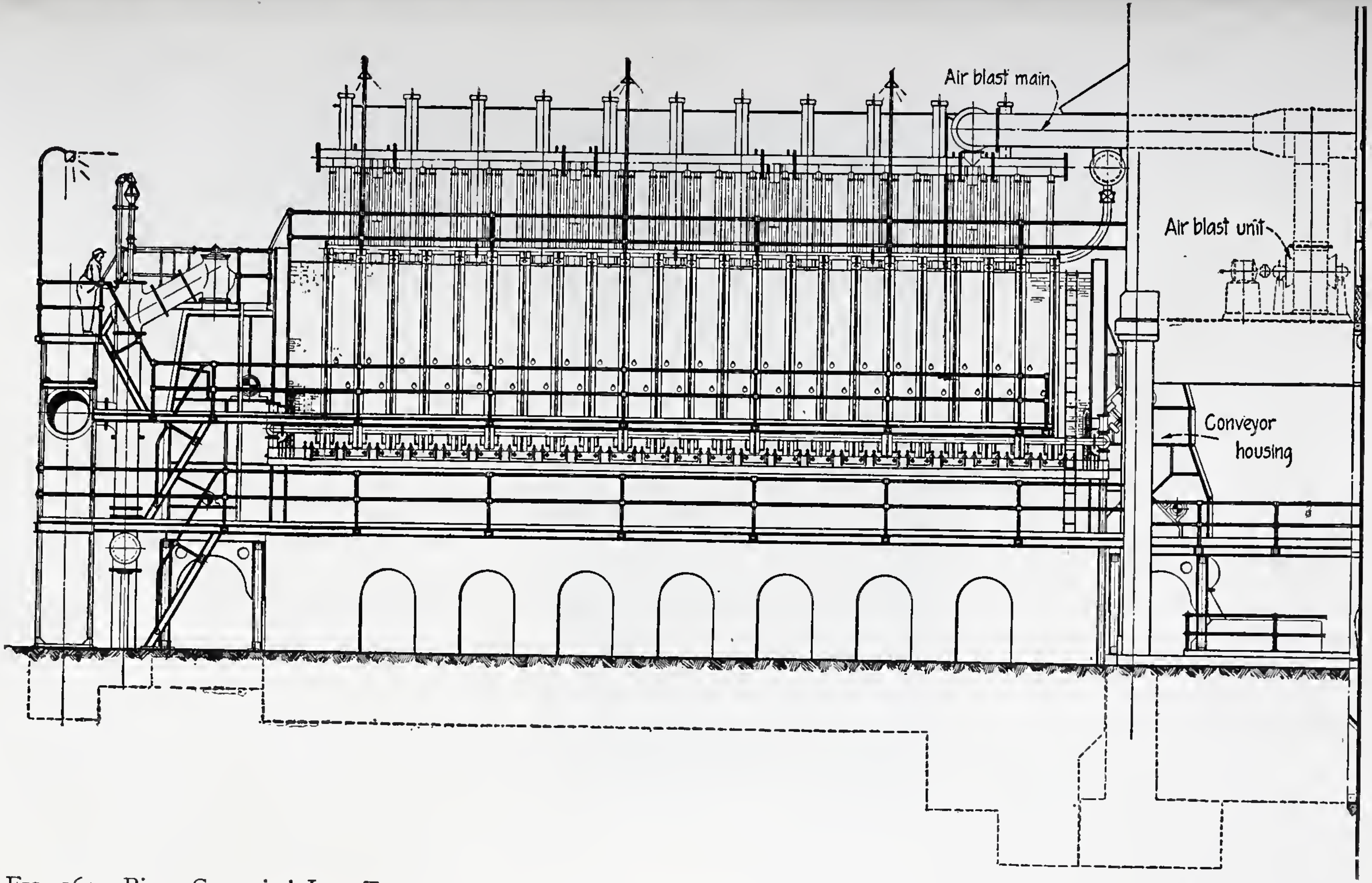

FIG. 164.—Piron-Caracristi Low-Temperature Carbonizing Installation, Drawing of Exterior View of Oven, from side opposite that of Fig. 163.

and each containing three separate conveyors 3 feet in width. Each oven consists of two chambers, an upper and a lower one, each about 45 feet long. Cast iron housings, projecting beyond the brickwork settings at both ends of the retorts, enclose the shafts and sprockets for the conveyors and have openings for coal feed, coke discharge, and gas outlet. Rectangular cast iron heating flues are placed transversely on the floor of the upper chamber thus passing through the lead bath which they heat to the required temperature. Between and over the heating flues is the molten lead bath, supported by the clay brickwork of the upper chamber floor. Water-cooled pipes extend crosswise through the brickwork about eight courses below the lead and serve to congeal any lead which may seep through the cracks or joints, and thus prevent its escape.

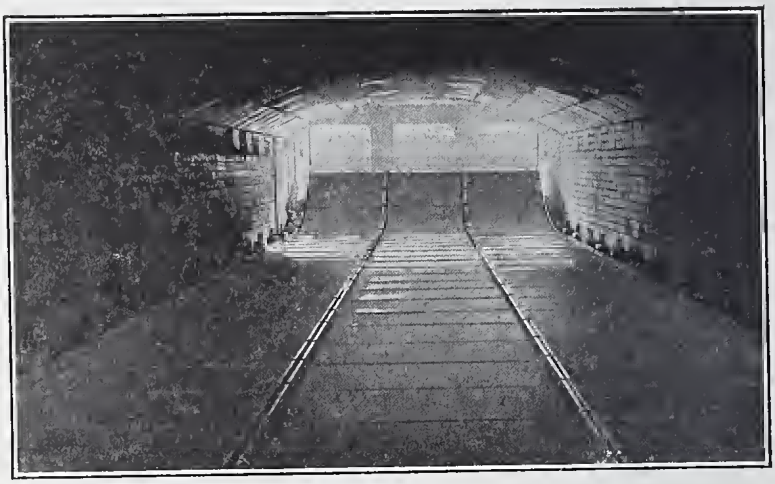

FIG. 165.—Piron-Caracristi Low-Temperature Carbonizing Oven, View of Interior showing Three Parallel Conveyors.

"As mentioned above, there are three main conveyors in each furnace; each consisting of flat links or platens of cast iron, 3 feet wide by 18 inches long, connected by steel pins. These conveyor plates are maintained at a temperature of 1200° F. Coal is fed in a layer one-half inch thick onto the feed end of the conveyor and is carried through the retort at such rate as to reach the other end in less than four minutes, which is said to be the time required for carbonization. The soft coke is dumped upon an auxiliary conveyor which travels in the lower chamber and in opposite direction to that of the main conveyor. This lower or return conveyor is in contact with the lower strand of the main conveyor and is said to assist in removing any coke which may stick to the latter. The coke falls into a discharge hopper from the lower conveyor directly below the coal feed to the upper conveyor.

"It is said to require only five horsepower to drive all the machinery of each unit, including the conveyors and the feeding devices.

"The Canadian plant, now being constructed, is rated at 400 tons of coal per day, all of the coke from which will be used in pulverized form under the power plant boilers. The ultimate capacity of another plant which is projected for the River Rouge plant of the Ford Motor Company is 4000 tons of coal per day. Part of the semi-coke from the latter is to be used as a substitute for Pocahontas coal in the Semet-Solvay coke ovens and part is to be burned in pulverized form. The semi-coke is of a peculiar soft, spongy structure which will not stand handling; it may be briquetted for domestic purposes or pulverized for power plant boilers.

"It is understood that the experimental plant (at Huntington, W. Va.) is not equipped with apparatus for measuring the exact quantity of gas or by-products obtained from distillation, so it must be assumed that the results quoted in 'Power' are laboratory results."

The Piron process ingeniously applies correct principles of low temperature carbonization. A thin layer of coal is heated quickly and uniformly, avoiding theoretically any overheating of gas and by-products. The amount of brickwork per unit of output rate appears to be large, as do also the opportunities for heat radiation losses. Presumably the experimental runs have overcome or satisfactorily adjusted any mechanical difficulties due to clogging of the moving elements, spillage of lead, coke, or coal, leakage around the cast iron boxed ends, leakage from distillation chamber to combustion flues, etc.

The capacity of each oven per day depends upon conditions, and particularly upon the amount of moisture in the material carbonized (see Figure 168, a chart by Caracristi showing his projected capacities of the large unit under construction at River Rouge, Michigan, as affected by moisture in the coal). The oven unit used in the experimental plant, said to be suitable for commercial use, 44 to 52 feet long, 14 feet wide, and 6 feet 5 inches high, is claimed to have a capacity of 25 tons per day. The outside dimensions of the brick work comprising such an oven unit are indicated to be 22 feet in width, 24 feet 8 inches in height (above the conveyor tunnel floor), and 45 feet in length. The brickwork and space requirements, as compared to high-temperature carbonizing, are apparently therefore excessive.

Much larger units are projected for the commercial installation at River Rouge, Michigan. Figures 162-167 illustrate the design and the progress of these installations.

An advance estimate by Caracristi of the costs of the process[13] shows, per net ton of coal, a total cost of $2.12, not including coal cost, but including distillation of the tar. Without the latter, his cost, per ton, is placed at $1.67. This includes $1.22 for operation and $.45 fixed charges.

The Del Monte Process, an early development in low temperature carbonization, operated for a time experimentally in Europe,[14] deserves

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[13] *Loc. cit.* in *Power.*

[14] *Glückauf,* 1914, 839.

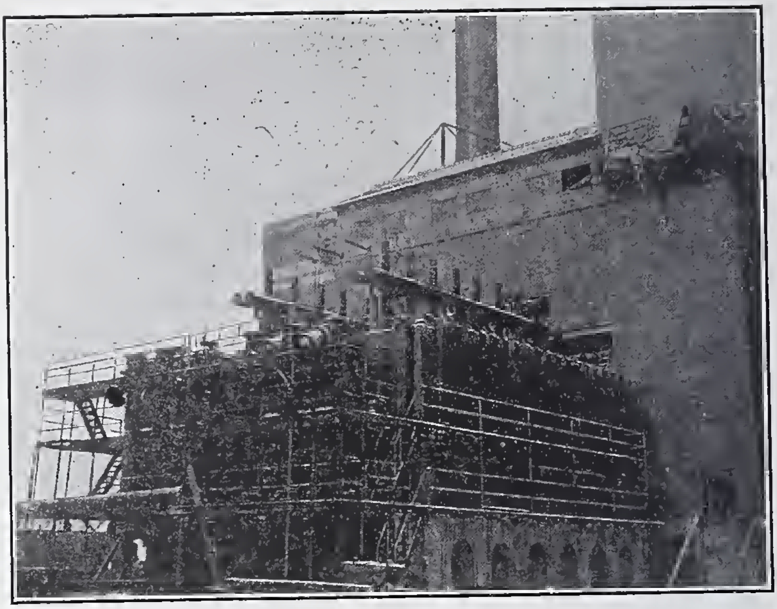

FIG. 166.—Piron-Caracristi Low-Temperature Carbonizing Plant, View of Walkerville (Ontario) Plant of Ford Motor Co. nearing completion.

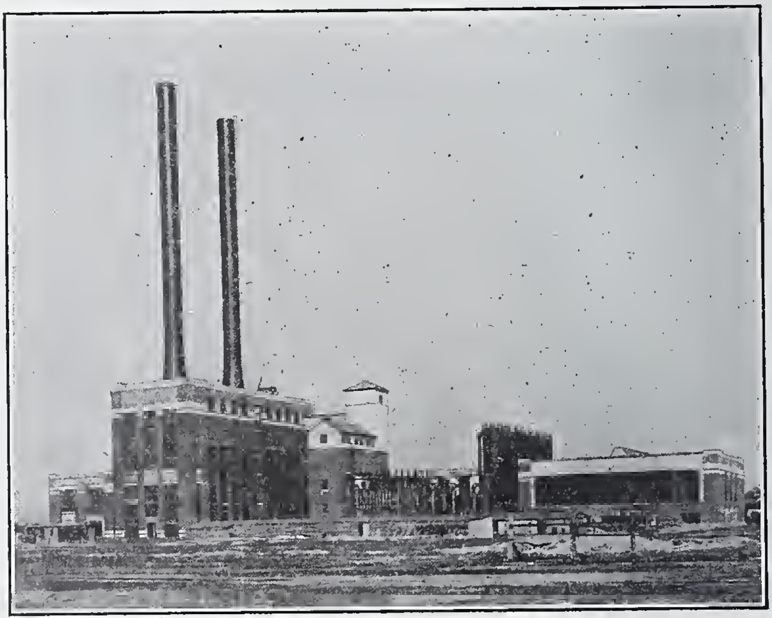

FIG. 167.—Piron-Caracristi Carbonizing Plant of the Ford Motor Co., at Walkerville, Ontario, General View of the Ovens and Adjoining Boiler Plant.

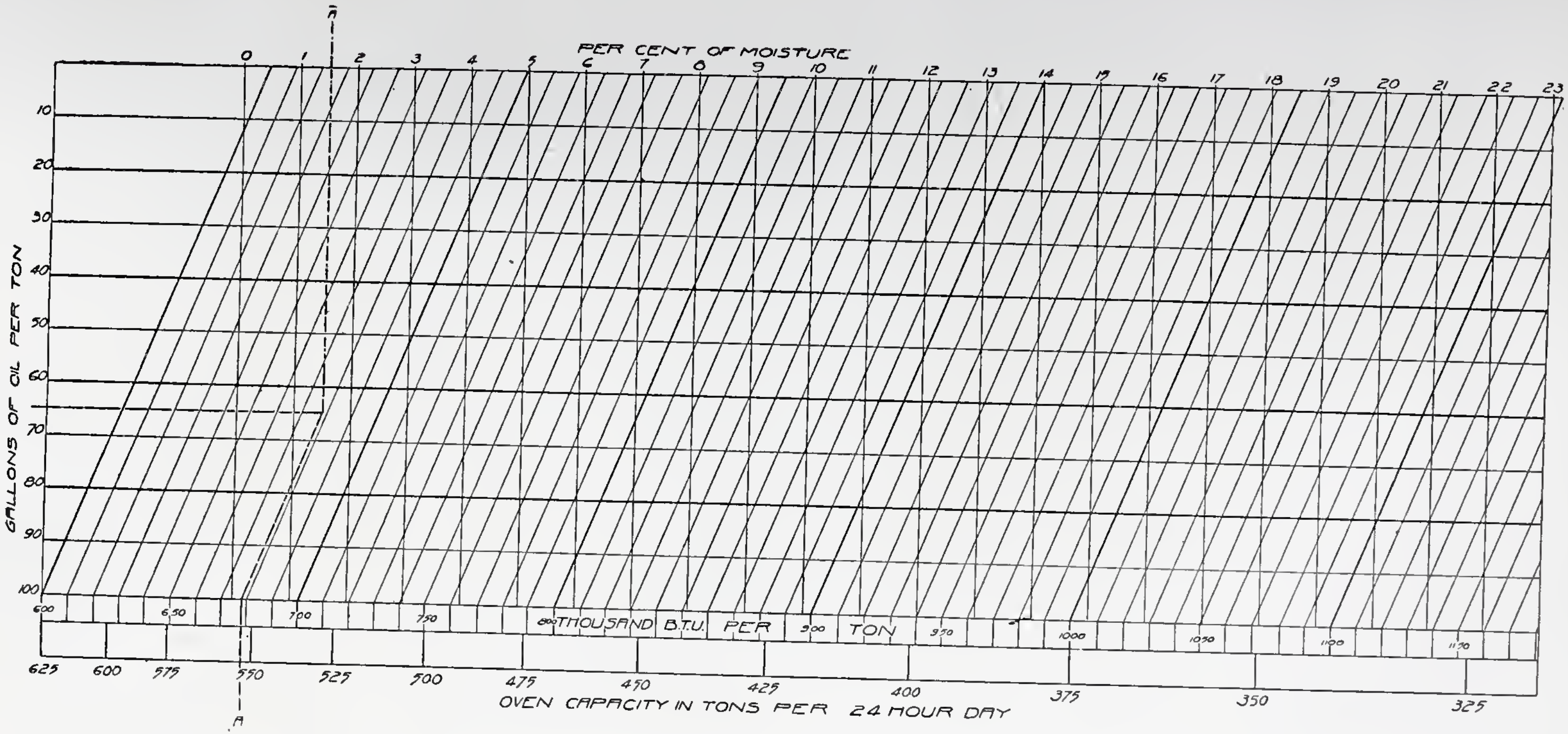

FIG. 168.—Chart (by V. Z. Caracristi) Showing Inter-relation of Varying Moisture in the Coal with Oven Capacity per Day (for Piron-Caracristi Plant of Ford Motor Co.).

mention as a forerunner of modern processes in which a worm conveyor moves the coal through a heated retort. In the Del Monte process, a current of coal gas or of an inert gas was maintained through the retort during carbonization.

The Greene-Laucks Process, an American development, operated on a semi-commercial scale, for demonstration purposes, by the Denver Coal By-Products Co., utilizes the worm conveyor principle in a vertical retort, with off-take for the gases through the hollow conveyor shaft.

It is described, in the light of its recent developments, by an American Gas Association Report (by C. V. McIntyre), as follows:

"The retort consists of a vertical cast iron cylinder 12 inches inside diameter by 12 feet high within which revolves a centrally located cast iron pipe 8 inches outside diameter. Around the latter and extending from the inner to the outer pipe are a series of helical screw flights about 12 inches pitch which receive the coal from a loading device at the bottom of the retort and screw it upward, in a layer about 9 inches thick on each flight, discharging it as coke at the top. The gases of distillation travel upward through the space between the top of coal and the bottom of the next flight and leave at the top through a pipe. No special vacuum is used as was the case in the former Greene-Laucks practice. Heat is applied by means of a gas burner system to the outside of the large pipe and to the inside of the center pipe, the temperature being maintained at about 750° F. in the shell.

"While there is undoubtedly some agitation of the coal mass during its upward passage, it can not be vigorous, or the coke would be broken and splintered, or dusty, whereas, it is said to come out in large pieces with very little braize."

Relatively large commercial development of this process is said to be in prospect, but definite initiation thereof has not, at this writing, been announced.

The "Carbo-Coal" Process (Figure 169), with little or no operating experience, and with a costly, and elaborate plant equipment, obtained, in 1918, under the urge of war necessities, the assistance of the U. S. Government, in building a large plant at Clinchfield, Va. This plant operated intermittently during a period of about two years, but, at the time of this writing, commercial operations are suspended, in order to develop improvements, experimentally, in the apparatus, especially the primary retort.

It is a duplex process, employing a low temperature stage in which the coal is moved continuously through horizontal cylindrical retorts (the primaries, Figure 169) by paddle wheel agitators, and a high-temperature stage in which briquettes made from the char of the first retorting are carbonized in inclined firebrick ovens (or secondary retorts).

The briquettes have been reported to be of good quality, but the operation was irregular and costly.

A series of papers by H. A. Curtis,[15] general manager, during the final period, of the Clinchfield plant, gives an excellent description, well illustrated, of the process, its method of operation at the plant named, and the reasons for the prohibitive costs resulting in temporary abandonment of the commercial venture.

The "Fusion" Rotary Retort, built in a demonstration plant at Cledford, Cheshire, England, utilizes a loose, tumbling iron breaker—a rod with "star" vanes attached—which serves to break up any hard deposits and insure free movement of the coal.

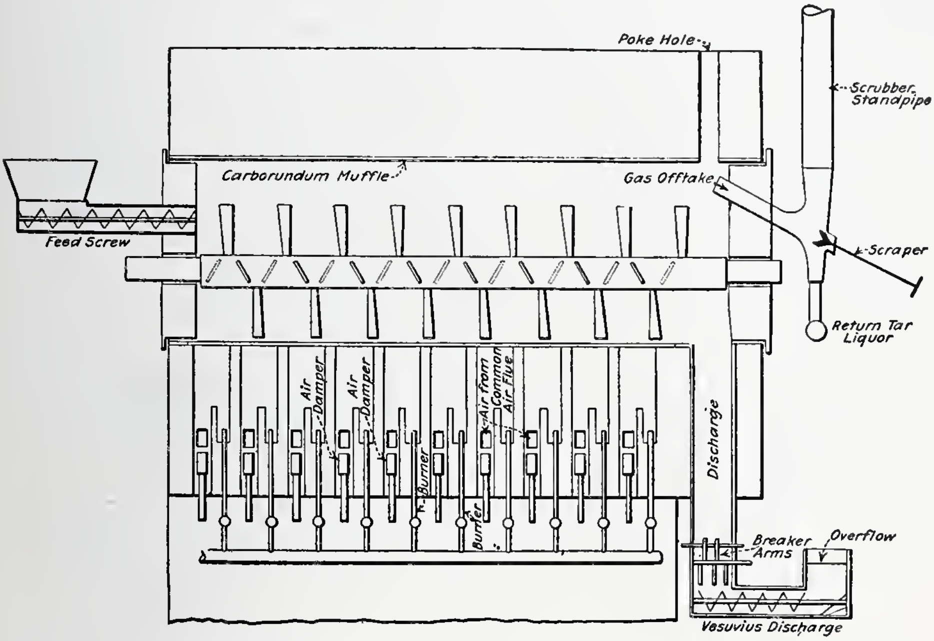

FIG. 169.—"Carbo-Coal" Process, Primary Retort.

The Pritchard-Whitaker Process promoted by the Acme Coal Products Co., 52 Vanderbilt Ave., New York, makes use of the principle of recirculation of the stripped coal gas through the interior of the retort during carbonization.[16]

The Products of Low Temperature Coal Carbonization.

Gas, Tars and Oils. In Chapter 11, pp. 313 and 322 a description of these products and an outline of their mechanism of formation has been given. The yields obtained vary so widely with the conditions of temperature and the operating method, and with the kind of coal used, that no definite limits can be stated. The oils, in general, are obtained in yields nearly double those of high temperature carbonizing, and the gas in yields one-third by volume but one-half by total B.t.u. per pound of coal.

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[15] *Chemical and Metallurgical Engineering,* 28 (1923), Jan. 3, 10, 17 and 24.

[16] Description, by the inventor, is to be found in *Chemical and Metallurgical Engineering,* 23, 664-6 (1920).

The possible yield of light oils, suitable for gasoline substitutes for motor use, is frequently exaggerated. It does not usually exceed 4.0 gallons per ton of coal carbonized, and these oils contain undesirable unsaturated constituents.

Coke or Semicoke. The coke also varies widely in quality according to the process, and the temperature, used. Low-temperature coke is often spongy and friable, bulky and light. Efforts have been concentrated, in certain processes, however, notably those of Parr, and Wallace, and the British "Coalite" method, to secure density and strength in the coke. Some of these have produced a coke of density and porosity approximately equal to that of high temperature coke, but of hardness and strength perhaps somewhat lower. When obtained from a process using agitation of the charge the coke is usually pulverulent or in small pieces.

Low temperature coke has sought generally the domestic market. It is unquestionably smokeless, if well prepared, and contains from 8 to 12 per cent. of volatile matter, giving it a desirable quality of easy ignition. This volatile matter is high in hydrogen, tending to increase the calorific value of the coke as compared to the usual high-temperature product. The lighter and more or less spongy grades of semicoke have, in a measure, the fault of excessively rapid burning, difficultly controlled.

As far as known to the author, no serious attempts to utilize low-temperature coke as a blast furnace or foundry fuel have been made in this country.

Chapter 14.

Miscellaneous Projects in Coal Carbonization.

Lignite Carbonization. Experiments have been under way during the last 10 years or more, in Canada and the United States,[1] on the improvement of the Western lignites, by carbonization.

The lignites of the United States and western Canada contain 20-35 per cent. of moisture and 24-30 per cent. volatile matter, in the raw state. The volatile matter is in large measure non-combustible, one-third to one-half composed of CO_2 and water of decomposition.

The reasons for the low efficiency of their use as fuels, in the raw or semi-dried condition, is therein apparent. Approximately 50 per cent. of the material as it reaches the combustion zone is inert—non-combustible.

The Canadian experiments led to the trial, in 1921-2, at Beinfait, Saskatchewan, of a continuous carbonizer, in which the lignite flowed over an inclined, heated, floor of a retort in a thin layer, and was thus deprived of a large part of its moisture and volatile matter. The development of this method of treating lignite was in charge of Edgar Stansfield, Chemical Engineer, and R. DeL. French, Engineer, designer of the retort. The experiments with this apparatus have been discontinued pending the incorporation of changes in the retort.

Other Canadian experiments are being carried on by the Province of Alberta, at Edmonton, in a small continuous carbonizer equipped to recover by-products.[2]

In continuation of investigations begun by E. J. Babcock, of the University of North Dakota, the Bureau of Mines (*loc. cit.*) has designed a continuous carbonizer to produce "lignite char" without recovery of gas or by-products. It is described and illustrated by Odell (*loc. cit.*). The raw lignite passes continuously downward (Figure 170) in an oven, or shaft of rectangular cross section, 6 feet long by 3 feet wide, and about 10 feet high. The shaft is restricted at two points to a width of 22 inches and tapers at the bottom to a 12-inch outlet. Jets of air are admitted to the shaft at levels just under the contracted parts, thus partially burning the lignite and furnishing heat for the carbonization. The irregular shape is designed to mingle more thoroughly the lignite and air during the movement downward. The char is recovered, by this means, in loose form, entirely uncoked, and in pieces of pea size and smaller. It requires briquetting for domestic use, but may be applied direct on special grates, under boilers, or burned in pulverized form. The yield by weight is 42-48 per cent., and the efficiency or percentage of B.t.u.'s recovered in the char, 55-60 per cent. The char has a B.t.u. value of 9,200-10,400 depending on the ash content. The costs of the process are relatively low, owing to the high capacity of this form of carbonizer and its low first cost.

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[1] Bulletin 89, Bureau of Mines, "Economic Methods of Utilizing Western Lignites," by E. J. Babcock, 1915; Technical Paper 178, Bureau of Mines (advance manuscript copy), "Notes on Lignite," by S. M. Darling, 1918; Report of Lignite Carbonizing Experiments at Grand Forks (N. Dakota) in 1922, Bureau of Mines Report of Investigations No. 2441, 1923, by W. W. Odell; "The Carbonizing and Briquetting of Lignite," by S. M. Darling, report published (1915) by the Government of the Province of Saskatchewan, Canada; "Lignite Char," by O. P. Hood, *Mechanical Engineering*, May, 1923; Report of the Lignite Utilization Board of Canada, for 1921, Montreal, Can.

[2] Now under the direction of Edgar Stansfield, Engineer.

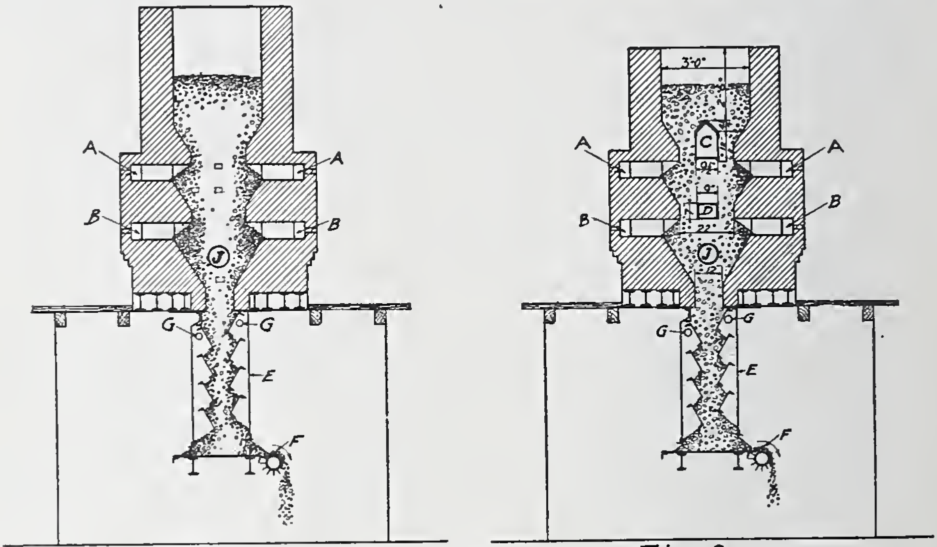

Fig. 1 Fig. 2

Fig. 170.—Lignite Carbonizer of W. W. Odell (from Bureau of Mines Report of Investigations No. 2441, 1923).

The economic value, to the Western fuel-consuming regions, of thus rendering the immense deposits of lignite available, has been mentioned in Chapter 2, pp. 38-9.

The Coking of Anthracite-Bituminous Coal Mixtures. In order to utilize to better advantage the fine sizes of anthracite coal, and the washed culm from the large accumulations about the mines, proposal has been made, and experiments[3] carried out, for carbonizing a mixture of about 60 per cent. anthracite with 40 per cent. bituminous coking coal. Although anthracite coal alone has no coking property, a mixture such as this, coked in a by-product oven yields a coherent residue, capable of being shipped and handled without degradation and suited well to domestic fuel purposes.

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[3] D. Markle, Transactions Amer. Inst. of Mining and Metallurgical Engineers, 1921.

The gas yield from such a mixture is materially larger than would be obtained from the proportionate quantity of bituminous coal, and is more than enough to furnish the necessary fuel. for carbonizing.

The rate of coking, in an oven, with this mixture, is faster than with bituminous coal alone, and costs are thus reduced in some measure; they remain, however, prohibitive, if standard by-product coke ovens or vertical retorts are used, owing to the high cost of these installations and the lower revenue from gas and by-products with this material than from the usual bituminous coking coal.

Another method, recently worked out, by other investigators on an experimental scale, consists in briquetting a mixture of about 80 per cent. anthracite with 20 per cent. bituminous, with a binder, and carbonizing the briquettes. A cheaper form of carbonizing retort may be utilized for this purpose, and it is found that the briquettes hold together remarkably well. They give promise of furnishing an excellent domestic fuel, entirely smokeless, substituting well the ordinary anthracite, in all essential qualities, and at a cost permitting competition with the domestic anthracite sizes.

Oil-Coal Amalgams and Their Use in Coal Carbonization. There has been manufactured on a semi-commercial scale, under patents of Walter E. Trent[4] an intimate mixture of about 20-25 per cent. fuel (petroleum) oil and 75-80 per cent. fine bituminous coal dust called an "amalgam." The process has for its object the reduction of ash content in low-grade high-ash coals and refuse, and the formation therefrom of a high-grade fuel in the "amalgam." The experimental operation has shown that by the addition of oil to a slurry of finely pulverized coal in water, a separation of the coal from its slate and shale impurities occurs, the latter not "amalgamating" with the oil.

This amalgam-forming process may be applied to the slimes of coal washeries, otherwise very difficult to dehydrate. The amalgam may be made with a water content of only 6-8 per cent. When such slimes are to be handled at washeries near coking plants, proposal has been made, and put to test experimentally, to charge the oil-coal amalgam into coke ovens in admixture with the regular coal charge. It has been found that with not over 10 per cent. amalgam the coke quality remains unaffected and by-product yields are increased.

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[4] U. S. Pats. 1,420,163-4-5 (1922). Descriptive articles on process in *Chem. and Metall. Engineering,* 25 (1921), Aug. 3; *Coal Age,* 21 (1922), June 8, p. 953.

Low-Temperature Carbonization, to Furnish Part of the Mixed Coal Charge to By-Product Coke Ovens.

A proposal to utilize low-temperature carbonization as an adjunct to a by-product coking plant, so as to furnish the low-volatile material for admixture in the charge to improve the coke quality from the ovens, has been made and is being experimented upon by one of the large steel companies in the Pittsburgh district.[5] By partial carbonization of high volatile coal in this way, a residue is obtained of 10-15 per cent. volatile matter, which when pulverized, mixed with the high volatile coal, and charged to the standard by-product coke oven, has the property, displayed by low volatile coking coals, of improving the strength and porosity of the coke.

The low temperature carbonizing retorts may in this case contribute high B.t.u. gas to enrichment of the main gas output. The tar would require separate collection, owing to its distinctive character.

A similar proposal has been made in connection with plans for the installation of the Piron Low Temperature Carbonization Process for the Ford Motor Co. (see p. 393), the residue in part to be mixed with high-volatile coal for charging to coke ovens.

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[5] According to Report of the Carbonization Committee, Amer. Gas. Assoc., 1923, p. 61 (C. V. McIntyre).

Chapter 15.

The Application of the Products of Coal Carbonization.

Gas. The subject of the industrial and domestic application of coal gas has been treated in Chapter 4, and that of its composition and formation in Chapters 5 and 11.

Tars and Oils. Many of the uses of tar and its products have been outlined in Chapter 11 (pp. 321-330, Table 46 and pp. 335-7). The subject is too large to find space in a work devoted chiefly to the processes of coal carbonization.

The character, composition and mode of formation of the different kinds of tar have been set forth in Chapters 5 and 11.

The Application of "Benzol" as Motor Fuel.

Since the close of the World War, by far the principal share of the output of coke oven light oil, drip-oils and the light oil of tar, has been devoted, in the United States, to the preparation of "motor fuel," for internal combustion engines. The possible production by existing methods from the coal carbonized in by-product coke ovens in 1922 would have been 120,000,000-125,000,000 gallons of purified "motor benzol." The actual production of light oil in 1920, according to statistics of the United States Geological Survey,[1] was 109,700,000 gallons.

The so-called "benzol" prepared for motor fuel is a purified mixture of approximately 85 per cent. benzene, 10 per cent. toluene and 5 per cent. xylenes and homologues. Unsaturated compounds, traces of tar, and much of the sulphur compounds have been removed by washing with sulphuric acid and caustic soda, and by preliminary separation of "fore-runnings" which contain the principal part of the carbon-bisulphide of the light oil.

The distillation characteristics of "motor benzol" and an average motor gasoline, as shown in Table 57, illustrate the relative "carburetting" properties or ease of evaporation of the two.

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[1] "Manufactured Gas and By-Products, in 1920," by R. S. McBride, *U. S. Geological Survey,* Separate Chapter II, 35, Mineral Resources of the U. S., p. 441.

TABLE 57.

	Motor Gasolines I *	Motor Gasolines II †	Motor Benzol
	° F.	° F.	° F.
First drop	130	115	172
10 per cent.	...	187	...
20 per cent.	204	212	...
50 per cent.	263	264	...
70 per cent.	...	298	212
80 per cent.	...	320	...
90 per cent.	387	356	...
End point	442	426	284

* Average commercial motor gasoline of Washington, D. C., 4th Semi-Annual Motor Gasoline Survey, Bureau of Mines, July, 1921.

† Representative motor gasoline sold in Pittsburgh, Bureau of Mines, Report of Investigations, No. 2394, Sept. 1922.

While a small portion (3 to 8 per cent.) of the average motor gasoline distills below 172° F., the point of beginning of distillation of motor benzol, the distillation curve of benzol is flatter, and complete distillation occurs before 70 per cent. of the gasoline has distilled.

This illustrates the desirability of an admixture of gasoline with benzol to secure ease of ignition. For winter use, benzol motor fuels are frequently compounded with a portion of low-boiling "casing-head" gasoline or the like.

On the other hand the fact of complete distillation of benzol within a lower temperature range than that of gasoline shows its relative ease of carburetion.

W. O. Hinckley [2] has shown that motor benzol evaporates in about one-fifth the time required for a gasoline of the type shown above. The same authority states that in an engine test 36 horsepower were developed by benzol as compared to 34.5 horsepower under the same conditions by gasoline.

The heating value of benzene per gallon is 137,000 B.t.u. as against 113,500 B.t.u. for an average gasoline. As to radiator temperature, however, it has been found in comparative engine tests that no appreciable difference therein results, when the usual cooling means are applied.

With benzol a leaner mixture does the work of a richer mixture of gasoline, as carburetor adjustment in comparative engine tests has demonstrated. Under equal conditions mileage per gallon has been increased approximately 20 per cent. by use of benzol (as compared to gasoline).[3]

The true reason for the principal superiority of benzol as motor fuel is probably to be found in its "anti-knock" properties as shown by the researches of Thos. Midgely, Jr., in the laboratories of the General Motors Corporation.[4] The reaction velocity of combustion can in an important measure be controlled by the addition of small quantities of anti-knock compounds to gasoline. But, more pertinent here, benzene has the anti-knock characteristic—a considerably less velocity of combustion than has gasoline, and therefore submits to a higher compression than gasoline, without detonation. The higher-boiling constituents of motor benzol, viz., toluene and xylene, possess the anti-knock characteristic also in high degree.

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[2] *J. Soc. Automotive Engineers,* 11, 359-62 (1922).

[3] *Gas World,* 59, Coking Section, Sept. 6, 1913, p. 9, and Nov. 1, 1913, p. 15.

[4] *Jour. Ind. Eng. Chem.* 14, 849-51 and 894-8 (1922).

The expansion-ratio of the engine and the gear ratio at the rear axle can be increased, with such a fuel, without causing undue detonation or "knocking" so as to result in loss of power. Midgely states that 40-60 per cent. of benzene, in admixture, can suppress satisfactorily the detonation or "knock" of gasoline.

Thorough purification of benzol by acid-washing is, of course, necessary, to secure freedom from "gumming" tendencies.

Carbon, when formed at all from benzol, is more flocculent, and easier to blow out by the exhaust than when formed from gasoline. The principal part of the "carbon" formation is ordinarily due to the lubricating oil rather than the fuel. "Crank-case dilution" with unburned residues from the fuel has been found in comparative tests to be less with benzol.

Most of the benzol motor-fuels on the market contain from 30 to 50 per cent. of "motor benzol."

Coke.

The porosity of coke, coupled with strength, and its freedom from volatile matter of a smoke-producing character, make it especially well adapted for many fuel purposes, particularly in smelting operations. Consumers in many instances find it profitable, by reason of their specialized requirements, to pay the higher price necessarily demanded for this fuel.

Coke as a Blast Furnace Fuel.

Of prime importance is the application of coke in the blast furnace to smelt iron ore. Over 75 per cent. of the coke produced is so applied.

The properties of coke, giving it particular applicability to this purpose are in some degree a matter of disagreement among experts. Almost every blast furnace operating superintendent has his own opinions, differing from those of others, on what qualities characterize the most efficient cokes for the purpose in hand.

Certain it is, however, that coke made carefully and from suitable coals, in by-product ovens, has been proven to be of equal or superior efficiency in the blast furnace to that of bee-hive cokes. The investi-

TABLE 58.

Furnace No.	Pounds Coke Per Ton Iron	Tons Iron Per Day	Carbon in Coke Per Cent.	Kind of Method of Manufacture	Coke Operation	Total Charged	Gasified in Furnace	Gasified at Tuyeres	Per Cent. Total Carbon	Per Cent. Gasified Carbon
1	2,615	301	86.3	BH	Stonega	2,254	2,110	1,868	82.8	88.6
2	2,551	272	84.4	BP	Solvay	2,153	2,049	1,751	81.4	85.6
3	2,472	482	86.1	BH	Conn.	2,128	1,996	1,728	81.2	86.6
4	2,247	450	87.1	BH	Conn.	1,957	1,846	1,605	82.0	87.0
5	2,198	499	86.9	BH	Conn.	1,908	1,810	1,494	78.7	82.6
6	2,123	541	88.3	BH	Conn.	1,875	1,764	1,498	79.8	84.9
7	2,115	360	84.3	BP	Solvay	1,782	1,683	1,427	80.1	84.8
8	1,996	490	86.3	BP	Koppers	1,722	1,611	1,298	75.4	80.6
9	1,936	376	85.7	BP	Solvay	1,659	1,557	1,305	78.8	83.7
10	1,905	393	88.7	BP	Solvay	1,690	1,575	1,252	74.1	79.5
11	1,901	517	85.5	BP	Koppers	1,625	1,524	1,280	78.8	84.1
12	1,863	504	86.6	BP	Koppers	1,614	1,513	1,230	76.2	81.3
13	1,780	426	84.9	BP	Koppers	1,511	1,414	1,124	74.4	79.5
14	1,742	503	84.6	BP	Koppers	1,474	1,382	1,133	76.9	82.0
15	1,716	542	87.1	BH	Benham	1,494	1,396	1,194	80.0	87.0
16	1,715	585	84.6	BP	Koppers	1,451	1,357	1,114	76.7	82.2
17	1,702	543	87.5	BP	Koppers	1,490	1,388	1,130	75.9	81.5
18	1,699	572	87.0	BP	Koppers	1,479	1,387	1,155	78.2	83.4
19	1,673	580	88.6	BH	Benham	1,482	1,384	1,182	79.0	85.0
20	1,658	590	88.3	BH	Benham	1,464	1,366	1,182	80.8	86.5
21	1,636	442	89.5	BP	Koppers	1,463	1,369	1,124	76.8	82.1
22	1,635	593	88.5	BH	Benham	1,447	1,349	1,124	77.7	83.4
23	1,624	592	87.3	BH	Benham	1,417	1,317	1,118	79.0	85.0
24	1,623	457	89.6	BP	Koppers	1,454	1,360	1,090	75.0	80.2
25	1,589	608	88.3	BH	Benham	1,403	1,307	1,100	78.5	84.2
26	1,584	466	89.2	BP	Koppers	1,413	1,324	1,057	74.8	79.9

NOTES.—BH = Beehive. BP = By-product. Conn. = Connellsville.

gation of H. P. Howland[5] on this subject has given actual operating results (Table 58) on the two kinds of coke which permit no other than the above conclusion.

Results presented also by H. A. Brassert in another paper[6] confirm these facts.

Uniformity and regularity of quality in the coke used form a large factor in successful operation, and these qualities by-product coke especially well provides. The facility of control, inherent in the by-product coking method, both by conditions of oven operation, and by suitable variation of coal mixture, well enables by-product coking to meet this requirement.

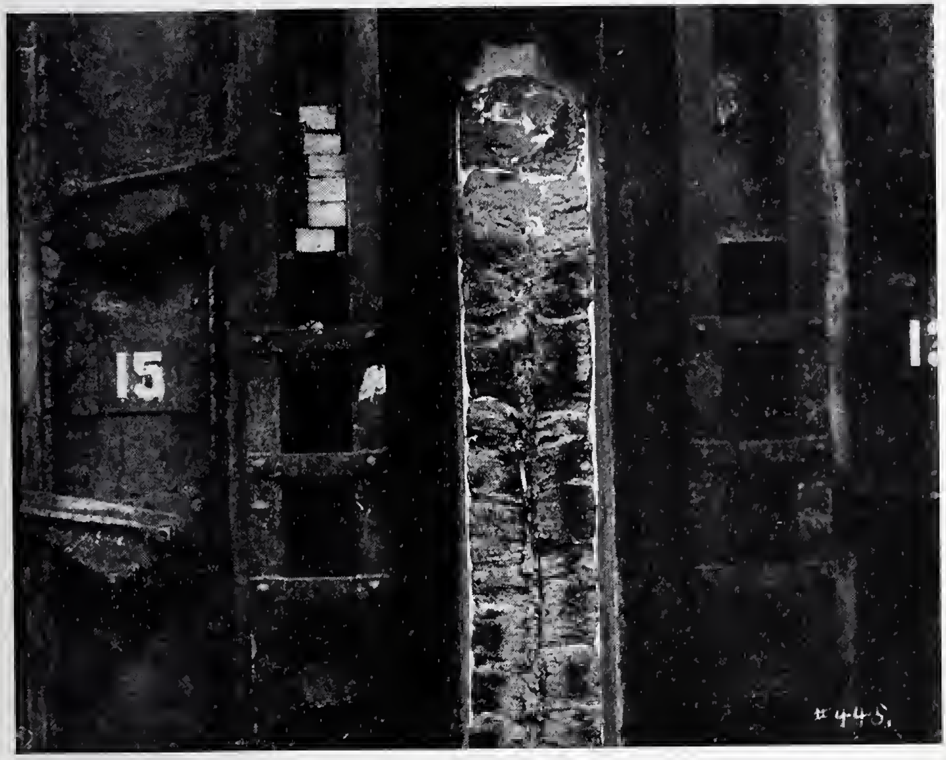

Fig. 171.—Coke Standing in By-Product Coke Oven, after Coking has been Completed, Showing Formation of the Pieces and Divisional Core in the Center.

Such methods of control of coke quality, especially by choice of coals and their mixture, are treated in thorough manner by F. W. Sperr, Jr., in a paper presented to The Franklin Institute[7] in 1918, accompanied by excellent illustrations of coke sections.

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[5] *Bull. Amer. Inst. Min. Eng.*, Mar. 1916, p. 627. Table 58 presents a summary of his results.

[6] *Iron Trade Rev.*, 54, 951 (1914).

[7] *Jour. of the Frank. Inst.*, Aug. 1918, pp. 133-163; see also, Ramsburg and Sperr, *idem.*, 1917, 392-430.

The porosity of coke, when accompanied by a sufficient thickness of cell wall, lending strength, is unquestionably a quality of much importance. Strength, i.e., resistance to abrasion and crushing, is needed by coke in handling and shipping as well as in bearing the burden in a furnace charge. The gases of the blast must have free passage.

Rate of combustibility, both in air and in CO_2, as varying among different cokes, has been urged in late years as a factor of importance in blast furnace operation. Further investigation is needed to settle differences of opinion on this question. Investigations by the Bureau of Mines[8] on this subject, correlated with actual measurements in commercially operated furnaces, appear to show very little difference between various grades of coke in the rate of burning in the tuyere zone. "The rate is so nearly the same that it has no appreciable influence on the furnace economy or operation." These investigators find also, in work not yet fully rounded out in all the necessary phases, that the rate of combustion in CO_2 in the upper zones of the furnace, has little apparent connection with general efficiency relationships of the cokes used.

Coke as a Domestic Fuel.

High temperature cokes are sold for domestic fuel purposes to a considerable extent. The total use for this purpose in the United States probably exceeded 4,000,000 tons in 1922. A full measure of success in applying coke fuel in this way depends on suitable sizing and careful preparation of the coke, and the choice of suitable conditions in its burning, mainly a fire box of ample volume and the maintenance of a bed of ashes beneath the fire.

Proper attention to these matters by the producers and sales agencies can secure large increase in this outlet for any surplus production of coke.

Other Applications of Coke are mainly as water-gas generator fuel, lime-kiln fuel and as a boiler fuel in the coke oven plants where produced.

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[8] Summarized by A. C. Fieldner, *Chemical and Metall. Engineering,* 29, 1052 (1923).

APPENDIX

TABLE 59: ANALYSES OF COAL TYPES,—FREQUENTLY USED IN, OR SUITABLE FOR BY-PRODUCT COKE OVENS

Note: Most of these analyses (except where noted) are of face samples taken in the mine; usually car deliveries to the consumer run 2 to 3 % higher in ash.

Name of Coal	PROXIMATE ANALYSIS (on coal as received)				ULTIMATE ANALYSIS (on dry coal)					Estimated coke yield (total) % on coal as received	Estimated gas yield, B. t. u. in gas per lb. coal
	Moisture	Volatile Matter	Fixed carbon	Ash	Carbon	Hydrogen	Oxygen	Sulphur	Nitrogen		
Western Penna.:											
*Connellsville .	2.40	29.90	60.48	7.22	78.50	4.67	6.82	.97	1.62	71.0	3100
Lower Connellsville	—	—	—	—	—	—	—	—	—	70.0	3200
Westmoreland .	1.00	35.00	57.60	6.40	—	—	—	.90	—	68.0	3350
*Pittsburgh . .	3.03	35.22	55.36	6.39	79.45	5.34	5.94	1.23	1.45	68.5	3300
*Freeport . . .	2.66	34.35	56.42	6.57	79.13	5.34	6.18	1.02	1.58	69.0	3300
*Somerset (Orenda) . .	3.77	16.26	71.06	8.91	81.96	4.15	2.22	.81	1.60	81.0	2600
West Virginia:											
*Boomer . . .	2.96	33.57	59.18	4.29	82.45	5.32	5.36	.80	1.65	69.0	3300
Cabin Creek (Kanawha) .	2.70	31.30	59.79	6.21	80.38	4.69	6.79	.59	1.17	71.0	3300
*No. 2 Gas . .	2.52	34.86	56.42	6.20	80.86	5.15	5.16	.87	1.60	69.0	3300
*Fairmont . . .	2.51	37.66	53.25	6.58	78.63	5.29	6.56	1.23	1.54	66.0	3350
*Pocahontas . .	2.60	16.39	76.38	4.63	86.79	4.22	2.33	.78	1.13	81.0	2650
*New River . .	3.51	24.76	69.00	2.73	86.08	4.95	3.91	.60	1.63	75.0	2750
*Elkins	1.40	26.40	62.92	9.28	79.03	4.74	3.85	1.52	1.45	75.0	2850
Virginia:											
*Tazewell Co. (Seaboard) .	3.13	29.00	61.77	6.10	82.63	4.82	4.23	.60	1.42	71.0	3100
*Toms Creek .	2.29	32.87	59.62	5.22	82.67	5.05	4.78	.55	1.61	70.0	3200
Eastern Kentucky:											
*Elkhorn . . .	2.91	36.33	57.53	3.23	82.26	5.49	6.71	.57	1.64	66.0	3450
*Coxton	3.18	37.21	56.30	3.31	81.50	5.30	7.10	.96	1.72	65.0	3450
*Benham . . .	2.50	37.52	57.63	2.35	83.01	5.42	7.07	.53	1.56	65.5	3500
Tennessee:											
*Jellico	3.87	38.03	55.18	2.92	80.34	5.54	7.90	1.13	2.05	63.0	3400
Alabama:											
*Pratt Seam . .	2.20	28.83	62.88	6.09	81.69	4.97	3.86	1.66	1.59	72.0	3000
*Tuscaloosa . .	2.62	24.18	64.11	9.09	79.61	4.55	4.33	.66	1.52	75.0	2700
Illinois:											
*Franklin Co. (Orient) . .	9.93	33.13	48.77	8.17	74.47	4.84	9.22	.83	1.57	61.0	2900
Indiana:											
**Ayrshire . . .	12.31	35.05	46.54	6.10	75.87	5.19	9.15	1.11	1.72	60.0	2950
Colorado:											
*Trinidad . . .	4.29	36.51	52.03	7.17	77.24	5.12	8.09	.61	1.45	64.0	3150
Utah:											
*Sunnyside . .	4.06	37.99	49.89	8.06	74.95	5.43	8.49	1.20	1.53	63.0	3200

* Mine sample, analysis by U. S. Bureau of Mines.
** Car sample, average of 10 cars, analysis by U. S. Bureau of Mines.

TABLE 60: YIELDS PER TON OF COKE ON VARIOUS MIXTURES OF PITTSBURGH (HIGH-VOLATILE) AND POCAHONTAS (LOW-VOLATILE) COALS
(17-hour coking time, 18-inch oven)

Per cent Pittsburgh in Mix	20	40	60	80	100
Per cent Pocahontas in Mix	80	60	40	20	0
Yields per ton of coal:					
Furnace coke (tons)	.762	.734	.706	.678	.650
Coke breeze (tons)	.034	.038	.042	.046	.050
Tar (gals.)	5.5	6.5	8.0	9.8	12.0
Ammonium sulfate (lbs.)	17.0	19.0	21.5	24.0	26.0
Benzol (motor fuel) (gals.)	1.6	1.9	2.2	2.6	3.0
Surplus gas (M. cu. ft.)	6.1	6.4	6.7	7.0	7.3
B. t. u. in gas per lb. coal	2720	2890	3060	3230	3400
Surplus B. t. u. in gas per lb.	1590	1730	1870	2010	2150
Yields per ton of furnace coke:					
Coke breeze (tons)	.045	.052	.059	.068	.077
Tar (gals.)	7.22	8.85	11.33	14.44	18.47
Sulfate (lbs.)	22.30	25.88	30.44	35.38	40.01
Benzol (gals.)	2.10	2.59	3.12	3.83	4.62
Surplus gas (M. cu. ft.)	8.003	8.717	9.487	10.32	11.235
Surplus B. t. u. in gas (millions)	4.172	4.713	5.296	5.925	6.618
**Returns* (per ton furnace coke)					
Coke breeze	$ .090	.104	.118	.136	.154
Tar	.289	.354	.453	.577	.739
Sulfate	.669	.776	.913	1.061	1.200
Benzol	.336	.414	.499	.613	.739
Surplus gas	1.252	1.414	1.589	1.777	1.985
Total	$2.636	3.062	3.572	4.164	4.817
Coal required (per ton of furnace coke) (tons)	1.312	1.362	1.416	1.474	1.539
Cost of coal—per ton coke (assuming Pittsburgh at $7.00 and Pocahontas at $9.00)	$11.28	$11.17	$11.04	$10.91	$10.78

* Prices assumed are: Coke breeze $2.00, tar 4¢ per gal. (fuel value), sulfate 3¢ per lb. (allowing for acid cost), benzols 16¢ per gal., surplus gas 30¢ per million B. t. u. (fuel value).

TABLE 62: COKE PRODUCTION IN THE UNITED STATES, 1909–1923
(U. S. Geological Survey)

Year	Production of Bee-hive Coke (net tons)	Production of By-product Coke (net tons)	Total (net tons)
1909	33,060,421	6,254,644	32,231,129
1910	34,570,076	7,138,734	41,708,810
1911	27,703,644	7,847,845	35,551,489
1912	32,868,435	11,115,164	43,983,599
1913	33,584,830	12,714,700	46,299,530
1914	23,335,971	11,219,943	34,555,914
1915	27,508,255	14,072,895	41,581,150
1916	35,464,224	19,069,361	54,533,585
1917	33,167,548	22,439,280	55,606,828
1918	30,480,792	25,997,580	56,478,372
1919	19,043,000	25,138,000	44,181,000
1920	20,511,000	30,834,000	51,345,000
1921	5,538,000	19,750,000	25,288,000
1922	8,573,000	28,551,000	37,124,000
1923	17,960,000	37,527,000	55,487,000

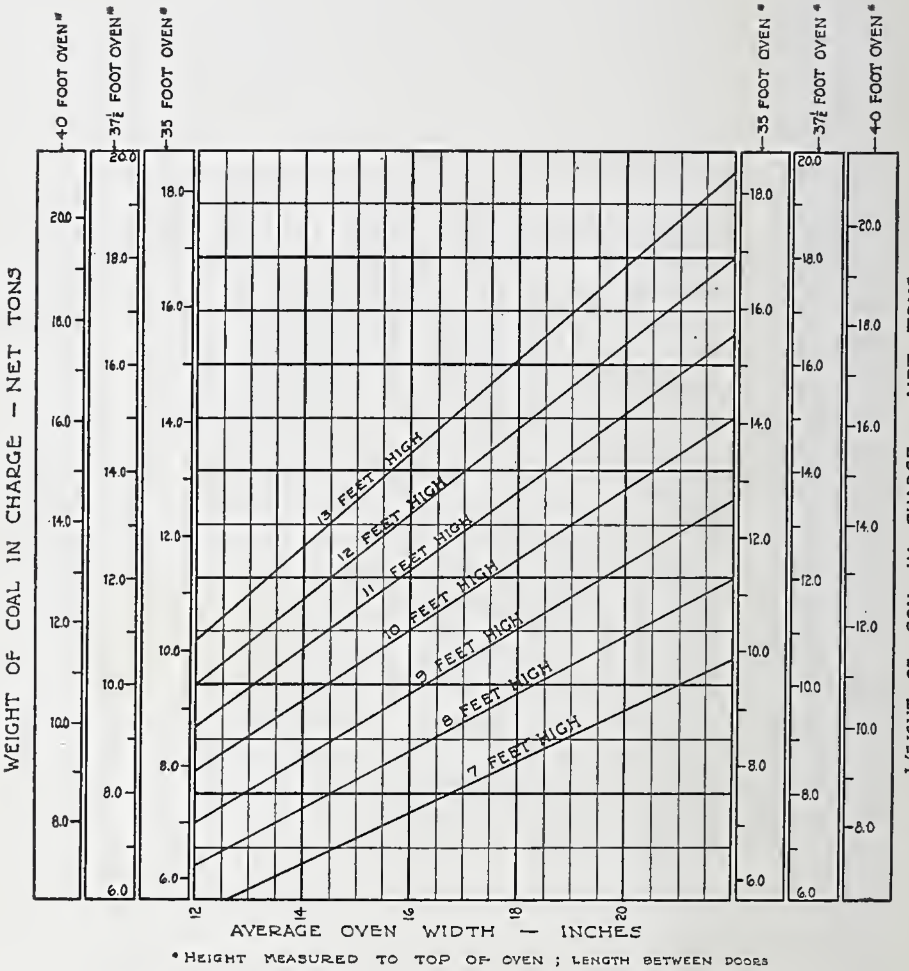

FIG. 172.—Chart to Show Weight of Coal Charge in By-Product Coke Oven, for Different Widths, Heights and Lengths.

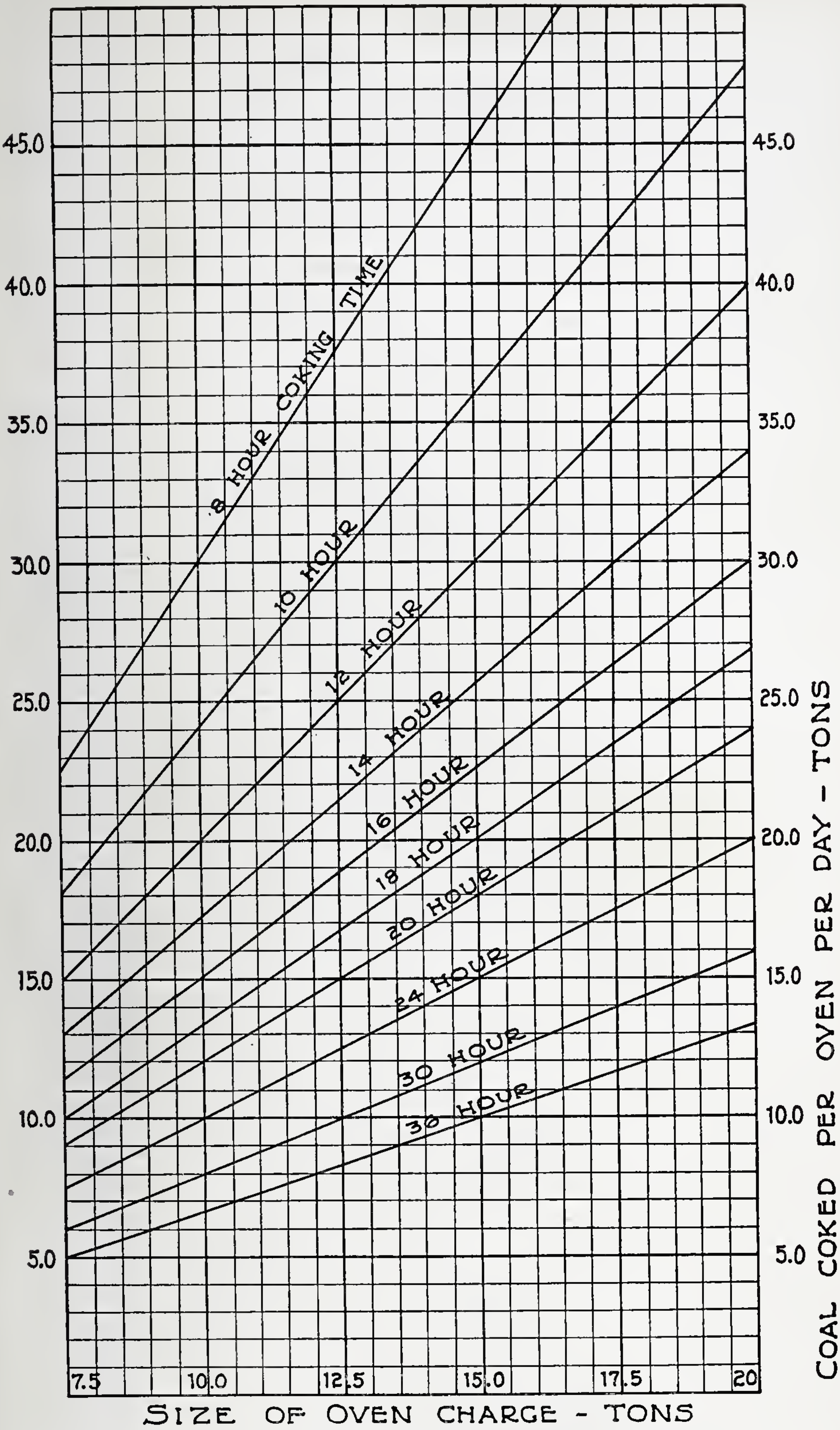

Fig. 173.—Chart to Show Variation in Oven Capacity (Coal Coked per Day) with Coking Time and Size of Oven Charge.

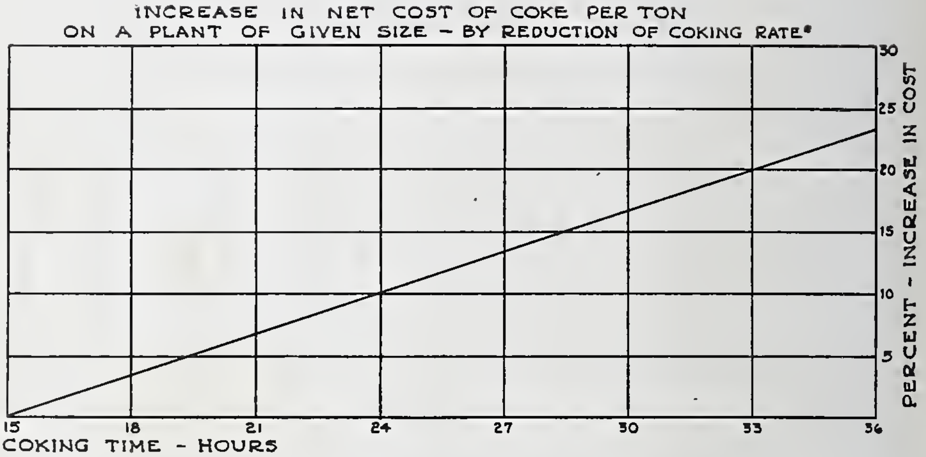

FIG. 174.—Chart Showing approximately, under average conditions, the Percentage Increase in Cost of Coke per Ton by Decrease of the Load Factor (for By-Product Coking).

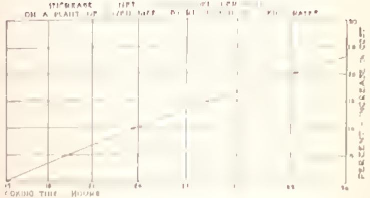

Fig. 174.—Chart Showing approximately [illegible] relation [illegible] the Percentage Increase in Coal [illegible] the Load Factor (for By-Product Coking).

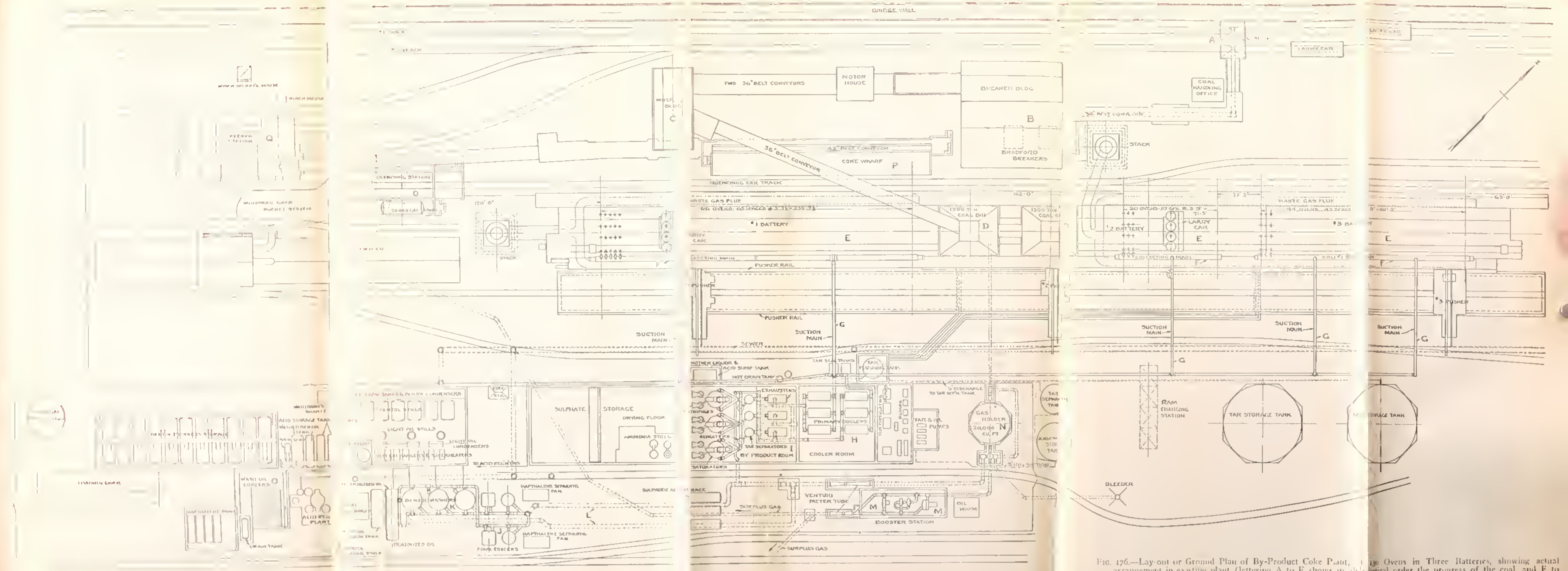

Fig. 176.—Lay-out or Ground Plan of By-Product Coke Plant, [illegible] 130 Ovens in Three Batteries, showing actual arrangement in existing plant (lettering A to E shows in alphabetical order the progress of the coal, and F to M the flow of the gas and by-products through the successive units of apparatus).

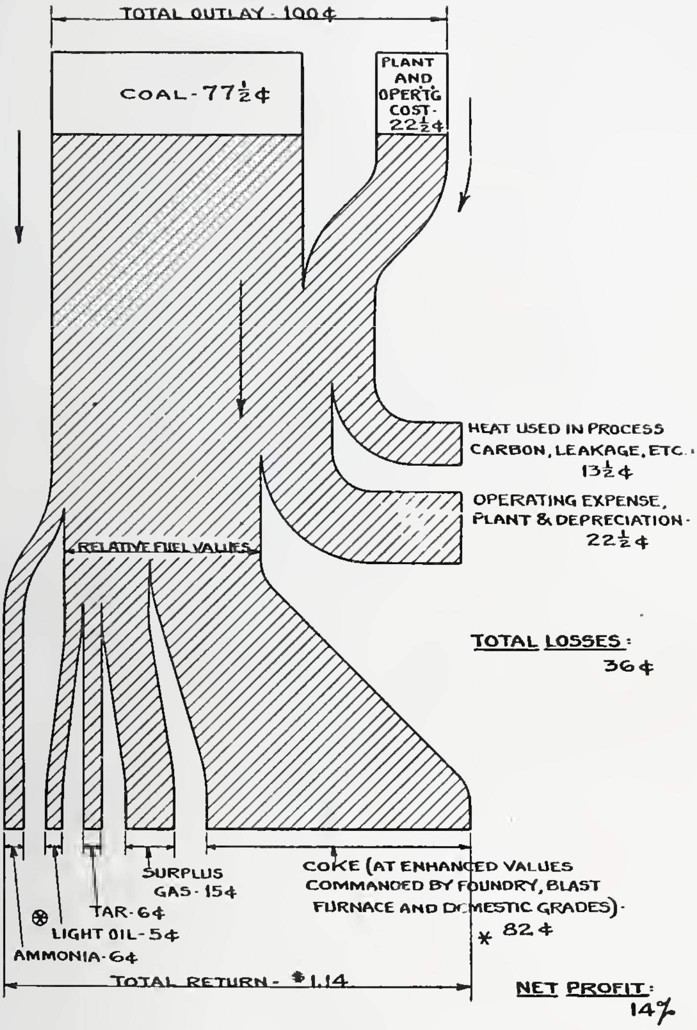

Fig. 175.—Chart Illustrating Commercial Revenues and Costs in By-Product Coking under certain assumed values, representing possible favorable conditions (drawn to show returns from one dollar of outlay in coal and plant costs).

TABLE 61: BY-PRODUCT COKE PLANTS IN THE UNITED STATES—

	1 Name of Operating Company	2 Location of Plant	3 Date Built	4 Number of Ovens	5 Type	6 Approx. Capacity per Oven per Day (Tons coal)	7 Oven Width (and taper)
1	Semet-Solvay Co.	Syracuse, N. Y.	1892 1896–03	12 28	Semet-Solvay	6.0	15″–17″ 16″–17″ 19″–21″
2	Cambria Steel Co.	Johnstown, Pa.	1895	60	Otto-Hoffman	6.0	17″–21″
			1899	150	Otto-Hoffman	6.0	17″–21″
			1904 1907	160	Cambria-Belgian	9.5	15″–19″
			1915	92	Koppers	11.5	17¾″–21¾″
			1918	90	Cambria	10.0	15″–19″
			1921	60	Cambria	11.5	17″–19″
			1921	88	Sem.-Solvay	17.0	16″–18″
			Total	700			
3	Semet-Solvay Co., for American Manganese Mfg. Co.	Dunbar, Pa.	1896	50	Sem.-Solvay	6.5	16″–17″
			1903	30	Sem.-Solvay	7.5	16″–17″
			1904	30	Sem.-Solvay	7.5	16″–17″
4	Allegheny By-Product Coke Co.	Glassport, Pa.	1897	120	Otto-Hoffman	6.0	19″–22″
5	Semet-Solvay Co., for Tenn. Coal, Iron & R. R. Co.	Ensley, Ala.	1898	90	Sem.-Solvay	5.0	16″–17″
			1899	30		5.0	16″–17″
			1902	120		6.5	16″–17″
6	Semet-Solvay Co., for National Tube Co.	Benwood, W. Va. (near Wheeling)	1898	30	Sem.-Solvay	5.0	16″–17″
			1899	30	Sem.-Solvay	5.0	16″–17″
			1901	60	Sem.-Solvay	6.5	16″–17″
7	New England Fuel and Transportation Co.	Everett, Mass. (near Boston)	1899	400	Otto-Hoffman	6.0	17″–22″
8	Hamilton-Otto Coke Co.	Koksotto (near Hamilton, O.)	1901	50	Otto-Hoffman	6.0	
			1909	50		7.5	
9	Semet-Solvay Co.	Detroit, Mich.	1901	30	Semet-Solvay	10.0	16″–17″
			1902	36		10.0	16″–17″
			1904	69		14.0	16″–17″
			1913	40		22.0	18½″–20½″
			1917	40		20.0	18½″–20½″
10	Michigan Alkali Co.	Wyandotte, Mich.	1902	15	Otto-Hoffman	9.0	
			1906	15			
			1916	24			
11	Carnegie Steel Co.	Farrell, Pa. (So. Sharon)	1903	212	United-Otto	9 to 10	17½″–20½″
12	Camden Coke Co. (Public Service Corp. of N. J.)	Camden, N. J.	1903	(100)*	United-Otto	7 to 9	17″–19″
			1906	50*			
			1921	37	Koppers	13 to 15	15½″–16½″
13	Semet-Solvay Co., for Central Iron & Coal Co.	Tuscaloosa, Ala.	1904	40	Semet-Solvay	10.0	16″–17″
			1906	20		13.0	18½″–20½″
14	Empire Coke Co.	Geneva, N. Y.	1904	30	Sem.-Solvay	8.0	Avg. 16″
			1909	16		11.5	
15	Zenith Furnace Co.	West Duluth, Minn.	1904	50	United-Otto	8.0	15½″–17″
			1916	15			

Corrected to March 1, 1924. (Arranged in Order of Age)

8 Height	9 Length	10 Heating System (Regenerative or Recuperative)	11 Coal Used Normally (Source and Mixture)	12 Coke Disposal	13 Gas Disposal	14
4′-7½″	30′-0″	Waste heat and Recuperative	High-volatile (32%)	Domestic and miscellaneous in mill	Miscellaneous mill use	Plant not in operation last part of 1922, or in 1923
6′-0″ 6′-0″ 6′-6″ 12′-0″	33′-0″ 33′-0″ 33′-0″ 30′-9″ 32′-0″ 38′-0″	Regenerative Regenerative Regenerative Regenerative Regenerative Regenerative Regenerative	40% high-volatile (Westmoreland, or similar) 60% low-volatile (Cambria Co.) (washed)	Blast furnace	Steel mills	
4′-7½″ 6′-7½″ 6′-7½″	30′-0″ 30′-0″ 30′-0″	Waste heat Recuperative Recuperative	Lower Connellsville (Pa.), 100%	Blast furnace 75% Domestic, 25%	Steel mills	
6′-0″	33′-0″	Regenerative	60% high-volatile (Pittsburgh seam) 40% low-volatile (Somerset)	Miscellaneous furnace & foundry 40% Domestic	McKeesport, Pa. City Distribution	Plant not in operation 1922
4′-7½″ 4′-7½″ 6′-7½″	30′-0″ 30′-0″ 30′-0″	Waste heat and Recuperative	Washed "Pratt" (Alabama) Medium high-volatile	Blast furnace	Steel mills	
4′-7½″ 4′-7½″ 6′-7½″	30′-0″ 30′-0″ 30′-0″	Waste heat and recuperative	80% high-volatile 20% low-volatile	Blast furnace	Steel mills	
6′-6″	33′-0″	Regenerative	West Va. high-volatile (originally used Nova Scotia washed slack)	Domestic, water gas, R. R. locomotive	City of Boston	
				Foundry and domestic, miscellaneous	City distribution and mill power	Plant not operating in 1922
8′-2″ 8′-2″ 8′-2″ 10′-9½″ 10′-9½″	30′-0″ 30′-0″ 35′-0″ 35′-4″ 35′-4″	Recuperative Regenerative	Mixture of high- and low-volatile averaging 28.4% volatile matter	Blast furnace (30%) Foundry (30%) Domestic (40%)	Total for city distribution	
		Regenerative		Miscellaneous industrial, and domestic	Public distribution and boiler firing	
7′-0″	43′-0″	Regenerative*	100% Klondyke (Lower Connellsville, Pa.)	Blast furnace	Steel mill	10 ovens out of 212 are 33′ long This plant idle in 1921–22
7′-0″ 9′-7″	33′-0″ 30′-10″	Regenerative Regenerative**	Pa. and W. Va. high-volatile	Domestic, water gas and foundry	Distribution in several cities by Public Service Gas Co. Pumped 70 miles under 20 lbs. pressure	*100 Otto ovens abandoned in 1922. **Heated by producer gas.
8′-2½″ 8′-2½″	35′-0″ 35′-3″	Waste heat Recuperative	Washed "Pratt" Seams (Ala.), Medium high-vol.	Blast furnace	Mill and town use	
7′-4″ 8′-11″	35′-0″	Waste heat Recuperative	Mixture of high- and low-volatile 75:25	Foundry and domestic	Distribution to several surrounding towns and cities	
8′-4¼″	33′-0″	Regenerative	High-volatile Penna. coal 100%	Furnace and domestic	City distribution	

TABLE 61: BY-PRODUCT COKE PLANTS IN THE UNITED STATES—

	1 Name of Operating Company	2 Location of Plant	3 Date Built	4 Number of Ovens	5 Type	6 Approx. Capacity per Oven per Day (Tons coal)	7 Oven Width (and taper)
16	Bethlehem Steel Co. (formerly Lackawanna Steel Co.)	Lackawanna, N. Y. (near Buffalo)	1904 1920 1923 (build'g)	94* 281 60 114	Otto-Hoffman Rothberg Sem.-Solvay Koppers New Type	7.0 18.0 23–24	Avg. 16″ Avg. 18½″ Avg. 14″
17	Philadelphia Suburban Gas and Electric Co.	Chester, Pa.	1904	40	Sem.-Solvay	10-11	15″–16½″
18	Milwaukee Coke & Gas Co.	Milwaukee, Wis.	1904–6 1920 1921	80* 50** 50	Sem.-Solvay Koppers Koppers	17–18 18–19 18–19	16″–18″ 16¼″–17¾″
19	Bethlehem Steel Co.*	Lebanon, Pa.	1904	90	Sem.-Solvay	10–12	
20	By-Products Coke Corp.	So. Chicago, Ill.	1905 1906 1910 1912 1915 1924 (build'g)	120 40 40 40 40 110	Sem.-Solvay Koppers "New type"	8– 9 11–12 15–16 15–16 15–16	15½″–16½″ 16″–17½″ 18″–20″ 18″–20″ 18″–20″
21	Bethlehem Steel Co.*	Steelton, Pa. (near Harrisburg)	1907 1918	120 60	Sem.-Solvay Koppers	10–12 16–17	16½″–18½″ 17″–19½″
22	Illinois Steel Co. (of U. S. Steel Corporation)	Joliet, Ill.	1908–09	280*	Koppers	15–16	17″–21″
23	Citizens Gas Co.	Indianapolis, Ind.	1909 1913 1914 1919	50 50 41* 40	United-Otto Sem.-Solvay Wilputte	7– 8 18–20	 18½″–20½″
24	Semet-Solvay Co., for Otis Steel Co. (formerly Cleveland Furnace Co.)	Cleveland, O.	1910 1915	49* 51	Semet-Solvay	10–12 14–16	15½″–17″ 20″–22″
25	Illinois Steel Co. (of U. S. Steel Corporation)	Gary, Ind.	1911 1913 1919	490 70 140	Koppers	16–18	17″–21″
26	Woodward Iron Co.	Woodward, Ala.	*1912 1921 1917 building in 1923	80 60 60 30	Koppers Wilputte Koppers	12–16 16–18	18½″–21″ 17″–19½″ 18½″–21″

CORRECTED TO MARCH 1, 1924. (ARRANGED IN ORDER OF AGE)—*Continued*

8 Heigbt	9 Lengtb	10 Heating System (Regenerative or Recuperative)	11 Coal Used Normally (Source and Mixture)	12 Coke Disposal	13 Gas Disposal	14
6′–4″ 10′–9″ 12′–6″	32′–3″ 36′–0″ 36′–4½″	Regenerative Recuperative Regenerative Regenerative	Mixture of high- and low-volatile—about 28% V. M.	Furnace	Steel mills	*Originally 188 Otto ovens
6′–7½″	35′–4″	Recuperative	Mixture varying 70 to 100% bigb-volatile	Blast furnace and domestic	City distribution	Mixture of producer gas and coke oven gas used to beat ovens
9′–0⅝″ 11′–8″	36′–0″ 30′–10½″	Rccuperative Regenerative Regenerative	Varying mixturc, from 65:35 to 80:20 high-and low-volatile (W. Va.)	Blast furnacc, foundry and domestic	City distribution	*Originally 160 Semet-Solvay **Koppcrs ovens of triangular flue type
8′–2½″		Recuperative		Furnace and foundry	Miscellaneous mill use	*These ovens built originally for Penna.Steel Co. and operated hy Semet-Solvay Co.
6′–6½″ 8′–2½″ 9′–9″ 9′–9″ 9′–9″	36′–0″ 36′–0″ 36′–0″ 36′–0″ 36′–0″	Waste beat Recuperative	70:30 to 65:35 higb-low-volatile, (Kingston, W. Va. and Pocahontas) Frequcntly with 10–20% Illinois	Furnace, foundry, domestic, water gas	City distribution	
8′–2½″ 9′–10½″	36′–0″ 37′–0″	Recuperative Regenerative	"Penn-Mary"-Pa. 26–27% Vol. matter (wasbed) Davis (W. Va.) low-volatile	Blast furnace	City of Harrisburg, Steel mill	*Built originally for Penna.Steel Co.
8′–9″	35′–0″	Regenerative	40–60 to 30–70 bigh-low-volatile Frequently 10 to 20% Illinois coal used	Blast furnace	Steel mill	*Tbese ovens were first Koppers in U. S. They were rehuilt on same foundations 1921–22 and made about 1 foot higber
10′–9½″	35′–4″	Regenerative Regenerative* Regenerative	"Milburn" and "Pond Creck," (W. Va. high-vol., 70% Pocahontas 30%)	Foundry and domestic	City distrihution	*This Semet-Solvay battery heated (sometimes) by producer gas
8′–2½″ 8′–2½″	33′–8″ 33′–8″	Waste heat recuperative	Mixture, bigb- and low-volatile, averaging 29.8% Vol.	Blast furnace	City distrihution	*This battery of 49 replaced 80 Rothberg ovens, dismantled
8′–9″	37′–0″	Regenerative	40:60 to 30:70 high-low-volatile (Elkhorn, Ky., and Pocabontas)	Blast furnace	Steel mill	
9′–10½″ 9′–10½″	37′–0″ 37′–6″	Regenerative	Pratt seams (Ala.) 100% (Volatile matter avg. 30%) washed, 8% water when cbarged	Blast furnace	Boiler firing, and miscellaneous industrial	*Original installation was 140 Koppers ovens; 30 were dismantled and 60 added in 1914: 60 added in 1921, replacing 90 abandoned.

Table 61: By-Product Coke Plants in the United States—

	1 Name of Operating Company	2 Location of Plant	3 Date Built	4 Number of Ovens	5 Type	6 Approx. Capacity per Oven per Day (Tons coal)	7 Oven Width (and taper)
27	Tennessee Coal, Iron & R. R. Co. (of U. S. Steel Corporation)	Fairfield, Ala. (near Birmingham)	1912 1919 1920	280 77 77	Koppers	18–20	18½″–21″
28	Coal Products Mfg. Co.	Lockport, near Joliet, Ill.	1912 1914	35 18	Koppers Wilputte	15–18	18½″–21″
29	North Shore Gas Co.	Waukegan, Ill.	1912	13	Sem.-Solvay	10–11	Avg. 19″
30	Central Indiana Gas Co.	Muncie, Ind.	1912	22*	Klönne	5	20″
31	Inland Steel Co.	Indiana Harbor, Ind.	1913 1914 1917	66 20 44	Koppers Koppers Koppers	18–20	18½″–21″
32	Semet-Solvay Co., for Kentucky Solvay Co.	Ashland, Ky.	1913 1916	54 54	Sem.-Solvay Sem.-Solvay	19–23	20″–22″
33	Republic Iron & Steel Co.	Youngstown, O.	1913 1915 building in 1923	68 75 61	Koppers Koppers New type	18–20 (Est. 25)	18½″–21″ Avg. 13¾″
34	Steel & Tube Co. of America*	Mayville, Wis.	1914 1917 1920	36 36 36	United-Otto United-Otto United-Otto	13.0	17″–20″
35	Bethlehem Steel Co.*	Sparrows Point, Md. (near Baltimore)	1914 1918 1920 1921	**120 60 60 60	Koppers	16–18 18–20	18½″–21″
36	Seattle Lighting Co.	Seattle, Wash.	1914	20	Klönne	3–5	16½″
37	Minnesota Steel Co. (of United States Steel Corp.)	Duluth, Minn.	1914	90*	Koppers	14–17	17″–21″
38	Bethlehem Steel Co.*	So. Bethlehem, Pa.	1915 1916	212** 212	Koppers	17–18	17¾″–21¾″
39	Laclede Gas Light Co.	St. Louis, Mo.	1915 1921	56 8	Koppers Piette	16–18 16–18	18½″–21″ 18½″–21″

Corrected to March 1, 1924. (Arranged in Order of Age)—*Continued*

8 Height	9 Length	10 Heating System (Regenerative or Recuperative)	11 Coal Used Normally (Source and Mixture)	12 Coke Disposal	13 Gas Disposal	14
	37′-0″	Regenerative	Mixtures of "Pratt" (Ala.) coals (medium high volatile), and "Blue Creek" (Ala.) medium-volatile	Blast furnaces and foundry	Steel mill	
11′-0″	39′-4″	Regenerative	Pittsburgh and Pocahontas mixture—27% vol. matter	Foundry and domestic	City distribution	
9′-0″	30′-0″	*Waste heat to boilers	100% Youghiogheny (Penna.) high-vol.	Gas producers and domestic	Public distribution	*Ovens heated by producer gas made in built-in producers, using hot coke and blown partly with flue gases
7′-0″	19′-0″		High-volatile	Domestic	Town distribution	*Resumed 1919 Closed down 1922
	37′-0″	Regenerative	70:30 high-low-volatile	Furnace	Steel mills	
10′-9½″	35′-4″	Regenerative	100% Marrowbone (Elkhorn) to 70:30, Elkhorn (high-volatile) and New River (low-volatile)	Furnace and foundry, 85%, domestic, 15%	Miscellaneous mill use	
8′-9½″		Regenerative	85:15 high-low-volatile	Furnace	Steel mill	
11′-10½″	40′-8″	Regenerative				
9′-1″	33′-2″	Regenerative	75:25 to 80:20 high-low-volatile	Blast furnace	Nodulizing of ore	*Merged 1922 with Youngstown Sheet & Tube Co.
8′-9½″	37′-0″	Regenerative	50–60% Penna. and W. Va. high-volatile, 40–50% Pocahontas	Blast furnace	Illuminating, City of Baltimore, mill fuel	*Originally built for Maryland Steel Co. **Displaced 200 United Otto ovens. Tar all burned in steel mills
7′-11″	27′-0″		Washington, high-volatile	Foundry and domestic	City distribution	
	37′-0″	Regenerative	60% "Klondyke" (Pa.) 40% Pocahontas	Blast furnace	Steel mill	*All in one battery. Tar burned in steel mill
8′-9½″	37′-0″	Regenerative	50–60% "Davis" and "Thomas" low-volatile, balance made up of "Elkins" (30 V.M.) and other high-vol.	Blast furnace and foundry	Steel mill	*Plant built originally for Lehigh Coke Co. **Replaced 300 Didier-March ovens, part of which were later operated for a time, then abandoned
8′-9½″ 8′-9½″	37′-0″ 37′-0″	Regenerative	Elkhorn (Ky.) 65–75%, Pocahontas (slack) 25%; Illinois 10–15% (intermittently)	Foundry, furnace domestic, water gas, zinc and lead smelting	Public distribution, City of St. Louis	

Table 61: By-Product Coke Plants in the United States—

	1 Name of Operating Company	2 Location of Plant	3 Date Built	4 Number of Ovens	5 Type	6 Approx. Capacity per Oven per Day (Tons coal)	7 Oven Width (and taper)
40	Indiana Coke & Gas Co.	Terre Haute, Ind.	1916 1919	30 30	Gas-machinery Koppers	16–20	15″–17″
41	Hanna Furnace Co. (formerly Dover By-Product Coke Co.)	Canal Dover, O.	1916	24*	Roberts		Avg. 14¼″
42	United Alloy Steel Corp.	Canton, O.	1916	47	Koppers	16–18	17″–19½″
43	Toledo Furnace Co.	Toledo, O.	1916	94	Koppers	16–18	17″–19½″
44	McKinney Steel Co.	Cleveland, O. (River Furnaces)	1916	204	Koppers	16–18	17″–19½″
45	Youngstown Sheet & Tube Co.	Youngstown, O.	1916 1918	204 102	Koppers Koppers	16–18	17″–19½″
46	Gulf States Steel Co.	Alabama City, Ala.	1916	37	Koppers	16–18	17″–19½″
47	La Belle Iron Works	Follansbee, W. Va.	1916	94	Koppers	16–18	17″–19½″
48	Semet-Solvay Co., for Wickwire Steel Co.	Buffalo, N. Y.	1917	60	Semet-Solvay	18–20	18½″–20½″
49	Seaboard By-Product Coke Co.	Kearney, N. J. (near Jersey City)	1917 1919	110* 55	Koppers	15–18	17″–19½″
50	Brier Hill Steel Co. (Youngstown Sheet & Tube Co.)	Youngstown, O.	1917	84	Koppers	16–18	17″–19½″
51	American Steel & Wire Co. (U. S. Steel Corporation)	Cleveland, O.	1917	180	Koppers	16–18	17″–19½″
52	Semet-Solvay Co., for Portsmouth By-Product Coke Co.	Portsmouth, O.	1917 1918	54 54	Semet-Solvay	19–21	20″–22″
53	National Tube Co. (U S. Steel Corporation)	Lorain, O.	1918	208	Koppers	16–18	17″–19½″
54	Semet-Solvay Co., for Ironton-Solvay Coke Co.	Ironton, O.	1918	60	Semet-Solvay	19–21	20″–22″
55	Semet-Solvay Co., for Chattanooga Coke & Gas Co	Alton Park, Tenn. (near Chattanooga)	1918	24	Semet-Solvay*	19–21	18½″–20½″
56	Carnegie Steel Co. (U. S. Steel Corporation)	Clairton, Pa.	1918 1919 building in 1923	640 128 366	Koppers (regular) Koppers New type	17–18 22–23	17″–19½″ 16″–18″
57	Minnesota By-Product Coke Co.	St. Paul, Minn.	1918	65	Koppers	16–18	17″–19½″
58	Colorado Fuel & Iron Co.	Minnequa, Colo.	1918	120	Koppers	17–19	17″–19½″

CORRECTED TO MARCH 1, 1924. (ARRANGED IN ORDER OF AGE)—*Continued*

8 Height	9 Length	10 Heating System (Regenerative or Recuperative)	11 Coal Used Normally (Source and Mixture)	12 Coke Disposal	13 Gas Disposal	14
11′-9½″	39′-0″	Regenerative	Mixture of 4th vein Indiana, and Pocahontas. Sometimes 100% Indiana	Furnace, foundry, domestic (50–60%)	City distribution	
13′-0″	40′-0″		90:10 mixture, high- and low-volatile	Blast furnace		*Not operating in 1922. Probably abandoned
8′-9½″	37′-0″	Regenerative	80:20 mixture, high- and low-volatile	Blast furnace	Mill use	
8′-9½″	37′-0″	Regenerative	Elkhorn 35%, Pond Creek, Eagle, and other W. Va. high-volatile 45%, Pocahontas 20%	Blast furnace	City distribution	
8′-9½″	37′-0″	Regenerative	80:20 Mixture, high- and low-volatile	Blast furnace	Mill use	
8′-9½″	37′-0″	Regenerative	80:20 mixture, high- and low-volatile	Blast furnace	Steel mills	
8′-9½″	37′-0″	Regenerative	Ala. coals, averaging 27 vol. matter	Blast furnace	Steel mill	
8′-9½″	37′-0″	Regenerative	Penna. high-volatile with 10–20% Pocahontas	Blast furnace	Steel mills	
10′-9½″	35′-4″	Regenerative	Mixture averaging 28.1% volatile	Blast furnace	90% miscellaneous mill use 10% to city	
9′-10″	37′-6″	Regenerative*	Pittsburgh seam (high-volatile) and Clearfield District (low-volatile) various mixtures	Water gas, foundry, domestic	All to city distribution	*2 batteries heated by producer gas
8′-9½″	37′-0″	Regenerative	80:20 high- and low-volatile	Blast furnace	Steel mill	
9′-10⅝″	37′-0″	Regenerative	70:30 high- and low-volatile	Blast furnace	Steel mill	
10′-9½″	35′-4″	Regenerative	Mixture averaging 31.6% volatile	Blast furnace	Open-hearth furnaces and miscellaneous mill use	
9′-10⅝″	37′-0″	Regenerative	70:30 high- and low-volatile	Blast furnace	Steel mill	
10′-9½″	35′-4″	Regenerative	Mixture averaging 31.6% volatile	Blast furnace and 11% domestic	Miscellaneous mill use	
10′-9½″	35′-4″	Regenerative	"Soddy" and other Tennessee coals 85–90%, volatile averages 28.1%	Blast furnace and foundry	City distribution	*Replaced 12 Roberts ovens abandoned
9′-10½″	37′-6″	Regenerative	Lower Connellsville high-volatile, 100%	Blast furnace	Steel mill	
		Regenerative				
11′-8¼″	40′-4½″	Regenerative				
9′10⅝″	37′-6″	Regenerative	80:20 mixture, high- and low-volatile Pittsburgh, Elkhorn and Pocahontas	Furnace, foundry, and domestic	City distribution	
9′-10⅝″	37′-6″	Regenerative	Colorado (Trinidad) high-volatile, 100%	Blast furnace	Mills	

TABLE 61: BY-PRODUCT COKE PLANTS IN THE UNITED STATES—

	1 Name of Operating Company	2 Location of Plant	3 Date Built	4 Number of Ovens	5 Type	6 Approx. Capacity per Oven per Day (Tons coal)	7 Oven Width (and taper)
59	Steel & Tube Co. of America (Youngstown Sheet & Tube Co.)	Indiana Harbor, Ind.	1919	120	Semet-Solvay	19–21	18½″–20½″
60	Ford Motor Co.	Dearborn, near Detroit, Mich.	1919	120	Semet-Solvay	19–21	18½″–20½″
61	Jones & Laughlin Steel Co.	Pittsburgh, Pa.	1919 1920	240 60	Koppers*	15–18	15¾″–18¼″
62	Rainey-Wood Coke Co.	Swedeland, Pa.	1919	110	Koppers	18–20	15¾″–18¼″
63	Providence Gas Co.	Providence, R. I.	1919	40	Koppers	16–20	15¾″–18¼″
64	International Harvester Co.	So. Chicago, Ill.	1919	88	Wilputte	15–18	15″–17″
65	Alabama By-Products Corp.	Birmingham, Ala.	1920 1923	50 25	Koppers	16–18	14¾″–17¼″
66	Semet-Solvay Co., for Schloss-Sheffield Steel & Iron Co.	N. Birmingham, Ala.	1920	120	Semet-Solvay	18–20	17½″–19½″
67	Pittsburgh Crucible Steel Co. (Crucible Steel Co. of America)	Midland, Pa.	1920	100	Koppers	16–18	15¾″–18¼″
68	Domestic Coke Corp.	Fairmont, W. Va.	1920	60	Koppers	16–19	15″–17″
69	St. Louis Coke & Chemical Co.	Granite City, Ill.	1921	80	Roberts	22–25	14″–16″
70	Donner-Union Coke Corp.	Buffalo, N. Y.	1921	150	Koppers	18–20	16″–18″
71	Chicago By-Product Coke Co.	Chicago, Ill.	1921	100	Koppers (regular)	18–20	Bottom: 15″–17″ Top: 14″–16″
			1922	5	Koppers New type	24–27	Bottom: 13¼–14¾ Top: 12¼–13¾
72	Weirton Steel Co.	Weirton, W. Va.	1923	37	Koppers New type	24–27	13¼″–14¾″
73	Battle Creek Gas Co.	Battle Creek, Mich.	Building in 1923	11	Koppers Small Gas Ovens, New type	12–13	Avg. 13½″

CORRECTED TO MARCH 1, 1924. (ARRANGED IN ORDER OF AGE)—*Continued*

8 Height	9 Length	10 Heating System (Regenerative or Recuperative)	11 Coal Used Normally (Source and Mixture)	12 Coke Disposal	13 Gas Disposal	14
10′-9½″	35′-4″	Regenerative	70% "Eagle" high-volatile, 30% Pocahontas	Blast furnace	Steel mills and city distribution	
10′-9½″	35′-4″	Regenerative	Mixture, 70:30 high- and low-volatile averaging 28.9% vol.	Blast furnace	90% public distribution	
9′-10″	37′-6″	Regenerative	100% Pittsburgh seams (33–34% vol. matter)	Blast furnace	Steel mills	*1 battery of triangular flue type. Tar all burned in open hearth and other steel mill furnaces
9′-10″	37′-0″	Regenerative	100% Lower Connellsville (Pa.)—Mixture of several mines (of W. J. Rainey Co.)	Blast furnace, small per cent domestic	One-third to city distribution, balance to steel mills and miscell.	
9′-10″	37′-0″	Regenerative	65–80 high-volatile Penna. and W. Va. 20–35 Pocahontas.	Foundry, water gas and miscellaneous	City distribution	Heated by producer gas
11′-0″	37′-0″	Regenerative	90% Benham (Harlan Co., Ky.) 10% Pocahontas	Blast furnace	Steel mill, and city distribution	
9′-10⅝″	37′-0″	Regenerative	Ala. coals	Furnace, foundry	Miscellaneous industrial	
9′-10⅝″	37′-0″	Regenerative				
10′-9½″	35′-4″	Regenerative	Ala. coals, averaging 29.0% volatile 6.1% moisture	Blast furnace and foundry	City distribution, boiler firing and mill use	
9′-10″	37′-0″	Regenerative	Penna. high-volatile 85–100%	Blast furnace	Open-hearth furnaces and other steel mill use	
9′-10⅝″	37′-0″	Regenerative*	Connellsville, Pa., 100%	Furnace, foundry and domestic	Miscellaneous industrial and domestic—gas delivered into existing natural gas mains in admixture	*Operated on producer gas firing
12′-9″	42′-6″	Recuperative	Franklin Co., Illinois, (various mines), Ayrshire, Indiana, with 10% Pocahontas	Blast furnace, foundry and domestic	Steel mills, and public distribution	
10′-0″	39′-0″	Regenerative	High-volatile 100%	Blast furnace, and domestic	Steel mill	
11′-8″	37′-0″	Regenerative*	85% Kentucky high-volatile with 15% Pocahontas (low-vol.)	60-70% for water gas, balance miscellaneous	Public distribution, City of Chicago	*Steam introduced in bottom of ovens to increase gas yield. **5-oven battery, heated by producer gas (Complete producer gas heating, for entire plant, being installed 1924.)
11′-8″	37′-0″	Regenerative**				
12′-6″	40′-0″	Regenerative	100% Pittsburgh seam (high-volatile)	Blast furnace	Steel mill	
	Approx. ½ of regular length Koppers coke oven	Regenerative*	Youghiogheny (Pa. high-volatile)	Domestic and water gas	City distribution	*To be heated by producer gas but equipped also to burn oven gas

TABLE 61: BY-PRODUCT COKE PLANTS IN THE UNITED STATES—

	1 Name of Operating Company	2 Location of Plant	3 Date Built	4 Number of Ovens	5 Type	6 Approx. Capacity per Oven per Day (Tons coal)	7 Oven Width (and taper)
74	Columbia Steel Co.	Salt Lake City, Utah	Building in 1923	33	Koppers New type	29–31 (est.)	13¼″–14¾″
75	Trumbull Cliffs Furnace Co.	Warren, Ohio	Building in 1923	47	Koppers New type	26–28	13¼″–14¾″
76	Diamond Alkali Co.	Alkali, Ohio	Building in 1923	23	Koppers New type	24–25	15″–17″
77	Northern Indiana Gas and Electric Co.	Fort Wayne, Ind.	Building in 1924	19	Koppers, New Type, Small Gas Ovens		
78	Troy Coke and Iron Corporation	Troy, N. Y.	Projected in 1924	44	Foundation		

Canadian Plants:

The by-product coking plants of Canada are purposely omitted from the above table; complete descriptive data for them in detail is not at hand. In general, however, these plants—as existing early in 1923—are the following: 110 Koppers ovens, Sault St. Marie, Ontario (Algoma Steel Corp.); 180 Koppers and 400 Otto (the latter idle or partly

CORRECTED TO MARCH 1, 1924. (ARRANGED IN ORDER OF AGE)—*Continued*

8 Height	9 Length	10 Heating System (Regenerative or Recuperative)	11 Coal Used Normally (Source and Mixture)	12 Coke Disposal	13 Gas Disposal	14
13′-0″	42′-6″	Regenerative	Utah Carbon Co. (Sunnyside Mines)	Blast furnace		
12′-6″	40′-8″	Regenerative	100% Pittsburgh coal	Blast furnace		
12′-6″	40′-8″	Regenerative		Lime kilns		

abandoned), Sydney, N. S. (Dominion Steel Corp.); 80 Wilputte ovens, Hamilton, Ont. (Steel Co. of Canada); 30 Foundation Co. or "American" ovens at Anyox, Brit. Columbia (Granby Consol. Mining and Smelting Co.); and 20 Semet-Solvay ovens contracted for in 1923 by Hamilton Gas Co., Hamilton, Ont.

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